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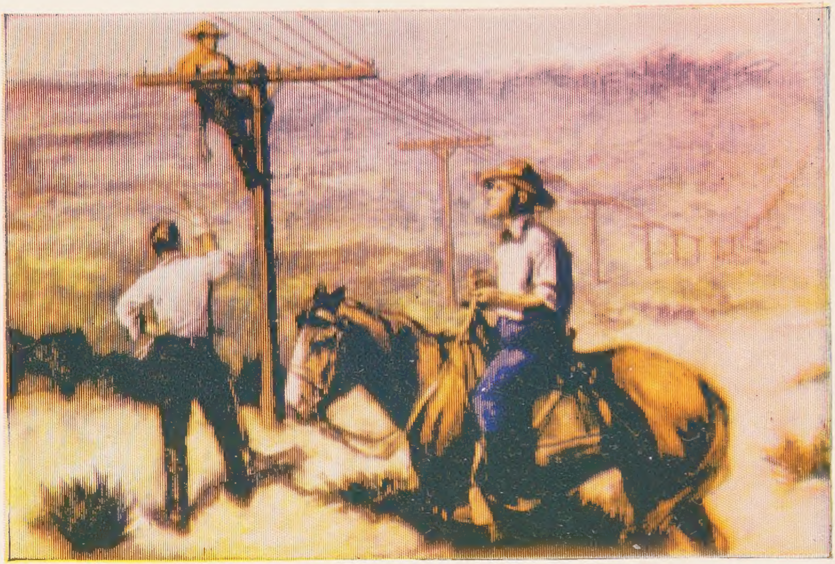
ELEMENTS OF
PHYSICS



THREE-COLOR PHOTOGRAPH TRANSMITTED OVER A TELEPHONE LINE

In transmitting a picture by a telephone line there are three operations: (1) The degrees of brightness of the different parts of the picture are used to produce variations of an electric current by means of a "photo-electric cell"; (2) The current is amplified by a "vacuum-tube amplifier" and the amplified current flows through the telephone line; (3) At the distant station the varying current acts through a "light-valve" and produces different degrees of illumination on a screen or photographic film, which is divided into parts corresponding to the parts of the picture. The process is so exceedingly rapid that the appearing of the whole picture is practically instantaneous. When the transmission is by radio, the varying current produces electromagnetic waves which produce varying currents at the distant station.

In transmitting a colored picture, like the above, three separate pictures in black and white, each due to one of the primary colors in the picture, are transmitted, and these are used to produce three blocks for printing the primary colors of the scene.

ELEMENTS OF PHYSICS

BY

A. WILMER DUFF, D.Sc.
PROFESSOR OF PHYSICS, WORCESTER POLYTECHNIC INSTITUTE

AND

HENRY T. WEED, B.S.
HEAD OF SCIENCE DEPARTMENT, GIRLS' COMMERCIAL HIGH SCHOOL
BROOKLYN, NEW YORK

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PREFACE

We shall not attempt in this brief Preface to discuss the general principles that have guided us in the writing of the present book, but some features in which it deviates from current practice may be noted.

After each numbered paragraph there are a few questions by which the student may test his understanding of what he has read. Frequently one who has read a paragraph without being conscious of difficulty has, in reality, failed to grasp some essential point in the statement. An attempt to answer a few questions before proceeding conduces to sound progress. The habit of self-examination in reading, a valuable habit in later life, should be encouraged by all means available. Possibly these questions may also be of assistance to less experienced instructors in physics.

Interesting pictures of the applications of the principles of physics help to awaken interest in physics as a study, and we have made a limited use of such aids, especially as regards aviation, the popular interest in which is likely to be great for a few years. Some interest in the personalities of eminent physicists is also helpful, but it is doubtful whether this is aroused, to any appreciable extent, by mere portraits. If, however, there is in the picture something that associates it directly with the text, something suggestive of the accomplishments of the person represented, then some more permanent impression through the eye may reasonably be expected. This expectation seems to be confirmed by remarks often made by adults in speaking of their early reading.

The authors wish to acknowledge their indebtedness to several friends for valuable assistance. Mr. J. Newton Gray, Head of the Science Department, James Madison High School, Brooklyn, prepared most of the Exercises and Problems. Mr. Willard B. Nelson, Head of the Science Department, Manual Training High School, Brooklyn, prepared many of the questions at the ends of paragraphs and read the page proof. Mr. Willard E. Lawton, Instructor in Physics, Worcester Polytechnic Institute, read the page proof and prepared the Index.

We are also under obligations to many manufacturing firms, publishers, and photographers, who have supplied materials for cuts: to *Popular Science Monthly* for the portrait of *Joseph Henry* and *Metal Diving Suit;* to *Scientific American* for *Testing an Airplane Member,* and *Ribbon Lightning;* to Bell Telephone Laboratories for the frontispiece and for *Television;* to *Commerce and Finance* for *Cotton Press;* to the Electric Vacuum Cleaner Company for the *Vacuum Cleaner;* to *Aero Digest* for Byrd's *America;* to the American Sugar Refining Co. for *Centrifugal Dryer;* to De Laval Cream Separator Co. for *Milk Separator;* to Victor Talking Machine Co. for *Phonograph Record;* to Fogg Art Museum, Harvard University, for the portrait of Count Rumford; to Carnegie Steel Co. for *Liquid Iron;* to the Bristol Co. for *Vacuum Pan;* to the Superheater Company for *Fire Tube Boiler;* to Westinghouse Electric & Manufacturing Co. for *Unit Generator* and the *Turbine Spindle;* to Mount Wilson Observatory for the *Mount Wilson Reflector;* to Bausch & Lomb Optical Co. for *Spectroscope, Projection Lantern, Opaque Projector, Compound Microscope, Prism Binocular;* to Cutler-Hammer Manufacturing Co. for *Electromagnet;* to General Engineering and Supply Co. for *Spot Welding Machine;* to General Electric Co. for *Multipolar D.C. Generator, Generator Stator, Generator Rotor, Commercial Transformer, Drum Armature,* and *Alternator.*

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ELEMENTS OF PHYSICS

CHAPTER I

INTRODUCTION

1. The Quest of Science.—From the earliest times to the present day, men have been trying to explain the happenings of everyday life. Many of the explanations devised by primitive people now seem to us fantastic. When it thundered the American Indians said the Great Manitou was clapping his hands, and the ancient Egyptians thought the wind was a wild animal and threw stones at it. We know a great deal more about such things now, owing to the efforts of many able men in the last few centuries, and what you will find in this book is a brief account of the greatest of their discoveries. Many facts have been ascertained, and relations between groups of facts, or **Laws of Nature,** as we call them, have been discovered. These laws have been applied in the construction and operation of trolley-cars, telegraph, telephone, and many other devices for making the world a more comfortable and more interesting place to live in. They also tell us why things happen, and we cannot neglect them with safety. Those who live in ignorance of them miss much of the interest of life.

By careful study, extending over hundreds of years, a great store of knowledge has been gathered regarding the world in which we live and even the distant stars. This knowledge, arranged in a systematic way, is called *science.* The aim of science is to understand the phenomena of Nature and make the knowledge useful to man. Science is divided into many branches. Thus there is a science of plants, a science of animals, and a science of the stars. What is the particular field of knowledge assigned to Physics? The answer to this question calls for the use of two terms, *matter* and *energy,* and these we shall now consider.

FIG. 1. "Physics" by Puvis de Chavannes (Boston Public Library) *

2. Matter.—All bodies consist of what we call matter. Different kinds of it are called *substances.* Many of these can be broken up into constituent parts, having properties that differ widely from those of the original. Water, a liquid, becomes two gases, oxygen and hydrogen. Salt, which gives an agreeable flavor to our food, is resolved into a metal sodium, and a gas chlorine, which was the first poison gas used in warfare. Oxygen, hydrogen, sodium, chlorine, and many other substances have not been broken up (except to a very minute extent in very recent times, § 509) and these are called *chemical elements.* But, much as substances differ, all bodies have certain properties in common. Some of these we shall consider in the next chapter.

3. Matter Is Indestructible.—Water and other substances can pass from the state of a *solid* to that of a *liquid,* and from a *liquid* to an invisible *gas,* but no particle of the substance is lost. Fuel can be burned and apparently leave only a little ashes. But gases are also produced, and while matter has been changed in form, none has been destroyed. Matter can take a multitude of different forms, but **the total quantity of matter is constant.** This principle, called the law of the *Conservation of Matter*, is the fundamental law of Chemistry, and it is also of fundamental importance in Physics.

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* From a Copley print; Curtis and Cameron, publishers, Boston, Mass.

4. Energy.—If there were nothing but matter in the world, nothing would happen. It would be a kind of dead world, somewhat like the moon or one of the dead stars of whose existence astronomers have found evidence. Matter in itself is inert, that is, it has no tendency to move or change in any way. The changes it undergoes are due to *energy*. We shall leave the definition of energy and how it is measured until later, but everyone has some idea what it means. It is what is needed for doing work of any kind. The *sun* is our great primary source of energy. Without it there would be neither vegetable nor animal life on the earth. Factories require the energy of *fuels* or *water-power*, both of which are derived from solar energy. Even to drive a nail requires the energy of motion we give to the hammer, and that comes from the food that we eat, so that it also is derived from the sun.

Energy must not be confused with *force*. To start the hammer in motion you push or pull on it, and in driving the nail, the hammer pushes on the nail. Pushes and pulls are forces. The force you exert on the hammer is a temporary action, but the energy of motion you give to the hammer stays with it, until it exerts another temporary force on the nail and transfers its energy to the nail.

5. Energy Is Indestructible.—Energy can be transferred from one body to another. It can also be transformed from one form of energy to other forms, and we divide Physics into parts that treat of the different forms of energy. For example, the energy required for lighting a town or driving trolley-cars often comes from water above a dam. This store of energy is due to the elevated position of the water. When some of it is transferred to the waterwheel or turbine, it becomes energy of motion of the wheel These forms of energy are called *mechanical energy*. The waterwheel turns a dynamo and produces energy of *electricity* and *magnetism*. This again is transformed into energy of *light* in an electric lamp or *heat* in an electric heater, and in all the different machines more or less energy goes into the form of *sound*. In all of these steps by

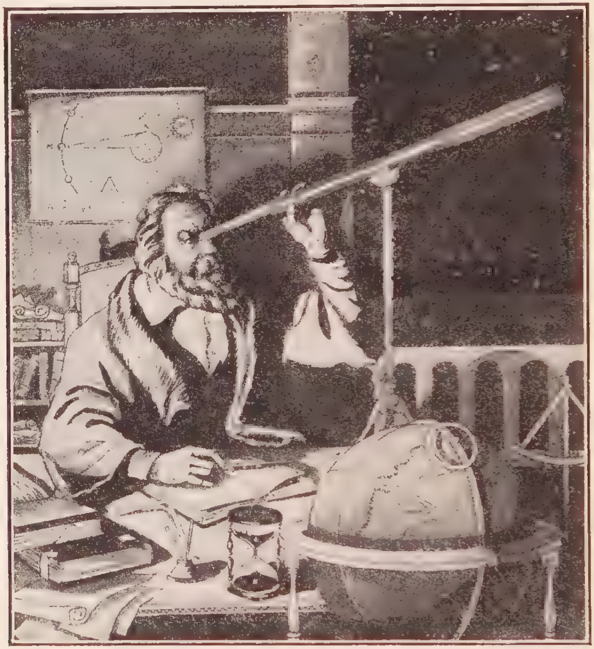

FIG. 2. Galileo Galilei (1564-1642) was the first great physicist and the first astronomer who scanned the heavens through a telescope. (Courtesy Cutter and B. E. Tweed Co.)

which energy passes from one body to another or changes its form, no new energy is created, and none is destroyed. Whatever changes energy may undergo, **the total amount of energy is constant.** This fundamental principle is called the law of the *Conservation of Energy.*

6. The Field of Physics.—The two things that remain constant in amount, matter and energy, form the subject-matter of Physics. Since it is the branch of science that studies the changes that energy produces in matter, we may define Physics as **the science of energy as related to matter.** That it is useful is evident, for all of our occupations are concerned with the various ways in which we can use energy to produce changes in matter. It also helps us to satisfy our natural desire to know how and why things happen as they do. There are very few boys or girls who have not wondered why turning a button in a wall produces a bright light, how we can talk with a friend miles away by means of long wires or hear music hundreds of miles away without any connecting wires, and why trolley-cars and automobiles go or sometimes do not go. One object of the study of Physics is to enable us to answer these and other questions.

7. Plan of Work.—For some time we shall be studying some important *Properties of Matter.* These may be divided into *properties of bodies* and *properties of substances.* For example, when you speak of something as large, massive, or heavy, you are referring to some particular body, such as a cannon-ball or a block of stone, but when you describe iron as hard and granite as brittle, you are discussing particular substances. Later, in *Mechanics,* we shall consider the relations of energy and work and the effects of forces. Thereafter in the study of *Sound, Heat, Light,* and *Electricity,* we shall be dealing with special forms of energy and the effects they produce in matter.

CHAPTER II

PROPERTIES OF MATTER

VOLUME. MASS. WEIGHT.

8. Volume.—Every body has a certain size, that is, it occupies or extends through a certain portion of space. A brick has length, breadth, and thickness, and by multiplying these we get its *volume*, or the amount of space that it occupies.

To be able to measure the dimensions of a body we must adopt some *unit of length*. The most familiar unit is the yard, or its subdivisions, the foot and the inch. A more scientific unit is the *meter*, which is equal to 39.37 inches. The subdivisions of the meter are the decimeter (dm.) or 0.1 m., the centimeter (cm.) or 0.01 m., and the millimeter (mm.) or 0.001 m. The only multiple of the meter that we need is the kilometer (km.) or 1000 m. The centimeter, which we shall have frequent occasion to use, is equal to about ⅖ inch (Fig. 3*a*).

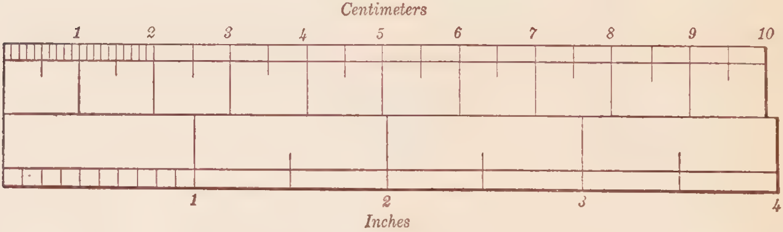

FIG. 3*a*. Comparison of Metric and English Measures

In the British system a variety of units are used in measuring areas and volumes, such as acres, square miles, quarts, and gallons. In the metric system the square of the unit of length is used as the unit of area, that is, the square meter, or square decimeter, etc. Similarly the cube of the unit of length is used as the unit of volume. Thus volumes are expressed in cubic meters (c.m.), or cubic decimeters (c.dm.), or cubic centimeters (c.c.) (Fig. 3*b*). The unit used in measuring liquids is the cubic decimeter, which is also called the *liter* (l.). It is slightly less than a quart. In Physics we frequently use the cubic centimeter (c.c.). It is equal to 0.001 liter.

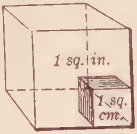

Fig. 3*b*. Comparison of Metric and English Measures

Define volume of a body. Name three English units of length. Name two scientific units. Name two English units of area. Name two English units of volume. How are the metric units of area and volume derived?

9. Mass.—A body is a portion of matter, and we often need to know how much matter there is in a body. For brevity, instead of speaking of the "quantity of matter" in a body we use the term "mass." But both of these terms are mere names, and mere names do not tell us much. What we need most to know about mass is how it is to be measured, and this is equivalent to asking: *What is the test of the equality of two masses?* In some cases we use a very simple and handy method. When we buy gasoline, we buy it by the gallon, since the volume of a liquid is very easily measured. We are then using volume as a measure of mass. We are not really anxious to get as much volume as possible when we buy gasoline by the gallon. In fact, the gasoline would be more easily stored if the same mass of it could be packed into a smaller volume. Measuring mass by volume applies only to bodies of the same substance. A gallon of gasoline has very different properties from a gallon of water. The question then is, how are we to compare the masses of two bodies, whatever the substances of which they consist may be? This question was considered a long time ago, and a simple method was found.

The oldest and simplest means for comparing the masses of two bodies in general is the *equal-arm balance* (Fig. 4). The beam of the balance is supported on a "knife-edge," which is midway between the ends of the beam. There are two other knife-edges, one at each end of the beam, and scale-pans hang from these. When the scale-pans are empty, the beam is horizontal. To find whether the masses of two bodies are equal, the bodies are placed in the scale-pans. If the beam remains horizontal when it is at rest, the masses of the bodies are equal. The mass of a certain standard body (pound or gram) is then taken as the unit of mass. A body that will just balance two such standard bodies is a body of two units of mass, and so on. Hence, as a basis for the measurement of mass we say: **The masses of two bodies are equal, if the bodies balance each other on an equal-arm balance.**

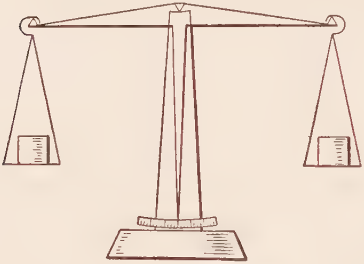

FIG. 4. Beam Balance

The unit of mass in English-speaking countries is the *pound*. For smaller masses the ounce, which is $1/16$ of a pound, and for great masses the ton, which is 2000 lbs., are more convenient. In other countries, the unit of mass is the *kilogram*. The gram is 1/1000 of a kilogram, and the milligram is 1/1000 of a gram. The unit for great masses is the metric ton, which is 1000 kilograms. It is worth remembering that the kilogram is equal to very nearly 2.2 lbs. The mass of a new nickel (5 cent coin) is 5 grams.

Define mass of a body. What instrument is used to compare the masses of bodies? Describe this instrument and tell how it is used. How can you tell when the masses of two bodies are the same? What is the unit of mass in English-speaking countries? In other countries? How many pounds make a kilogram?

10. Relation of Mass and Volume.—There is evidently some relation between the *mass* of a body and its *volume*. Two bodies of water of equal volumes have equal masses. The same is true of two equal volumes of lead. But a cubic foot of lead has not the same mass as a cubic foot of water.

To express the relation between mass and volume we use the term *density*. The density of a substance is defined as the mass of unit of volume of the substance, or

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

Thus, if we weigh a cubic foot of water, we shall find that its mass is 62.5 lbs. Hence its density is 62.5 lbs. per cu. ft. In this way a table of densities can be calculated.

If we find the volume of a body and look up its density in a table of densities we can calculate its mass, since

$$\text{mass} = \text{volume} \times \text{density}$$

We can also calculate the volume of a body if we know its mass and density, since

$$\text{volume} = \frac{\text{mass}}{\text{density}}$$

Thus the volume of a ton (2000 lbs.) of water is 2000/62.5 or 32 cu. ft.

Those who designed the metric units intended that the gram should be the mass of 1 c.c. of water at the temperature at which the density of water is greatest. The measurements made were not perfectly accurate, but the difference is so slight that we shall usually take the mass of 1 c.c. of water to be 1 g. From this it follows that the density of water, expressed in grams per c.c., is 1.

Do equal masses always have equal volumes? Do equal volumes always have equal masses? Define density. What mathematical relation exists between mass, volume, and density? What is the density of water in English units? In metric units?

11. Weight.—Everyone knows that a body above the surface of the earth will fall to the ground, if it is not supported in some way. A balloon may seem to be an exception, but it is supported by the air. This universal tendency of bodies to fall is due to the earth, which attracts all bodies toward itself. *Weight is the measure of the earth's attraction.* The force with which the earth attracts a cannon-ball is large, because the mass of the cannon-ball is large. The mass of a feather is small, and the earth's attraction for it is correspondingly small. The weight of a body also depends on how close the body is to the earth. We cannot, it is true, carry a body far enough above the earth to make much difference in its weight. But we believe, for reasons that will be stated later, that if a cannon-ball were far enough from the earth it would be as light as a feather is near the earth.

There is a simple relation between the masses of two bodies and their weights, *when the bodies are at the same place.* If the two bodies balance on an equal-arm balance, their masses are equal. Their weights are also equal, for the forces pulling on the beam to make it tilt one way or the other are the weights of the bodies, and neither force is able to overcome the other, so their weights must be equal. From this it follows that *when we are comparing the masses of two bodies by means of an equal-arm balance we are also comparing the weights of the two bodies at the place of observation.* Because of this relation between mass and weight, we take the weight of a body of unit mass as the unit of weight, and the word pound or gram is used for the unit of weight, as well as for the unit of mass. This means that if the mass of a body is 10 pounds mass its weight is 10 pounds weight.

Define weight. Does the weight of a body ever change? How can we compare the weights of two bodies?

12. Difference of Mass and Weight.—You will sometimes be likely to confuse mass and weight. They are, however, essentially different. Weight is a *force,* by which we mean something in the nature of a push or pull. When you speak of the mass of a body, you are thinking of the *amount of matter* in the body. The mass of a body is the same wherever the body may be. The weight of a body is slightly different at different places on the earth, and if the body were taken very far away from the earth its weight would be very small, while its mass would be unchanged. When you buy sugar, you want as much matter of that particular kind as possible. Its weight is of no advantage to you. But if you needed ballast for a ship, or a heavy keel that would hold a yacht upright in the water, you would be chiefly interested in the weight of the material.

It usually does not make much practical difference whether you speak of the mass or the weight of a body. When we say that a certain body is of 10 pounds' weight, we understand that its mass is 10 pounds. But there are cases in which it is necessary to be clear as to whether we mean mass or weight. For example, we say that the density of a body is its *mass* divided by its volume, for we do not think of the density of a substance as something that depends on how strongly the earth attracts the body.

What is the difference between mass and weight? Why do we use mass in defining density instead of weight? Is the mass of a body always the same? Is the weight of a body always the same?

13. Unit of Time.—In addition to the units of mass and length which we have defined, we need a unit of *time.* For this purpose we shall use the **second.** A solar day is the time interval between the passage of the sun over the meridian of a place (the moment when the sun is highest) and its next passage over the same meridian. It varies in length according to the time of year. The average length is called the *mean solar day,* and is divided into hours, minutes, and seconds; 1/86400 of this mean solar day is the *second.*

What other unit is needed besides the units of mass, force, and length? What name is given to it? How was its length fixed? What is a solar day? A mean solar day? A second?

14. Two Systems of Units.—The use of two different sets of units in Physics seems necessary. Everyone should know how to use the units of everyday life, such as feet, pounds, and seconds. These units are called *British units* because of their origin. The more scientific French units are usually called *metric units.* They are used, almost exclusively, in advanced work, and are likely to be adopted sometime, for ordinary use, in English-speaking countries. They have the great advantage of requiring only decimal fractions or multiples.

To avoid confusion it is necessary, in any problem that may arise, to *use a consistent set of units.* For example, it would be confusing to state the mass of a body in pounds and its volume in cubic centimeters. When we are using the British system we shall always use feet, pounds, and seconds, unless some other units are mentioned. This may be called the **f.p.s. system.** In the metric system we ordinarily use centimeters, grams, and seconds. This is known as the **c.g.s. system.**

What is the f.p.s. system of units? The c.g.s. system? What is the advantage of the c.g.s. system?

EXERCISES

1. What is weight? To what is it due?

2. What is the unit of weight in the English system? In the metric system?

3. What do the prefixes *milli, centi, deci, kilo* mean?

4. What is the unit of mass in the English system? In the metric system?

5. Is there any difference between mass and weight? Explain.

PROBLEMS

1. Express decimally 2¾ meters as decimeters, as centimeters, as millimeters, as meters.

2. A linoleum rug is 1 meter wide by 2 meters long. How many sq. dm. does it contain? How many sq. cm.? How many sq. m.?

3. Express 25,643 mm. as cm., as dm., as m.

4. How many cm. are there in an inch? How many inches in a meter? Reduce 0.75 yard, 0.125 foot, 2.3 inches to cm.

5. Define the meter. One c.c. of the human body weighs almost 1 g. What is your volume in c.c.? In liters? What is your weight in grams? In kilograms?

6. The cylinders of an automobile engine are 3 inches in diameter. What is their area in sq. inches and in sq. cm.?

7. The inside dimensions of a trunk are respectively 1.3 m. x 0.67 m. x 0.5 m. What is the area of each surface in sq. m.? In sq. dm.? In sq. cm.? What is the volume in cu. dm.? In cu. m.?

8. A train goes 60 miles per hour. What is its velocity in km. per hour?

9. What is the diameter in inches of the French 75 mm. guns?

CHAPTER III

PROPERTIES DUE TO MOLECULAR FORCES

15. Molecules and Atoms.—When you look at glass or smooth metal, or even examine it with a magnifying glass, you find it difficult to believe that there are any vacant spaces in the material. Yet if you heat it, it will become larger, and if you cool it, it will become smaller. It is not in reality continuous in structure, but is made up of countless minute particles, which are in ceaseless motion and only in contact when they collide. These particles we call *molecules.* When we heat the body, the molecules drive each other farther apart, and the volume increases. When we cool it they come closer together, and the volume of the body decreases. The addition of one pint of alcohol to one pint of water does not give one quart of the mixture, but only about 1.9 pints. This is because the molecules of the alcohol pack in between the molecules of water, and so the whole takes less space, just as a mixture of a pint of beans and a pint of sugar will not fill a quart measure.

Molecules are much too small to be seen by the eye or even by a microscope, except when great groups of them are united to form visible particles, but we know of their existence by indirect evidence, and we also know that they consist of still smaller parts, called *atoms.* It was formerly supposed that an atom could not be divided into still smaller parts, but the marvelous discoveries in Physics in the last few years have shown that atoms consist of *electrons* and *protons,* and we shall give some account of these later.

How do you know there are vacant spaces in matter? Of what does matter consist? Of what do molecules exist? What are the parts of atoms called?

16. Forces between Molecules.—We have already used the word force as a general term for any push or pull exerted by one body on another, including that attraction of a body by the earth which we call the weight of the body. There must also be forces of attraction between molecules, for if there were not, molecules would not cling together and form solids and liquids. We cannot measure the force between a single pair of molecules, because a molecule is too small to be seen alone, and the force between a single pair would be too small to be measured by any instrument we could construct. But we feel the effects of these forces when we try to change the shape of a solid body. For example, if we try to pull a wire apart, the forces between an immense number of pairs of molecules are lined up against us, somewhat as opposing teams are lined up in a rope-pull. Many of the familiar properties of bodies are due to these molecular forces, and we shall now consider some of them.

Why cannot we measure the force between two molecules? What proof have we that some force between molecules must exist?

17. Cohesion and Adhesion.—All bodies are composed of molecules, and in solids and liquids these molecules are held together by a force called cohesion. When the distances between molecules are very small, the force of cohesion is very great, but it acts only at very small distances. When a saucer has been broken it cannot be mended by pressing the pieces together. In welding two pieces of iron, the blacksmith forces them so closely together, by hammering them while white hot, that the weld is almost as strong as the original iron.

Cohesion is the force of attraction between like molecules. *Adhesion* is the force that is exerted between unlike molecules. A stick dipped into water comes out wet, because the water has adhered to the stick. Glue holds two pieces of wood together because it adheres strongly to both pieces. To make the joint strong, we must press the two pieces of wood very closely together, as adhesion, like cohesion, acts only through small distances.

What is cohesion? Why cannot a broken plate be mended by pressing the pieces together? What is welding? How is it done? What is adhesion? How does it differ from cohesion? Of what use to us is adhesion?

18. Elasticity.—We commonly call a rubber band elastic because it stretches easily. This, however, is not the meaning of elasticity as the word is used in Physics. *Elasticity* is here defined as the ability of a body to *return exactly to its former size or shape after being distorted.* It is not the ease with which it can be changed, but the ability to return to its former condition, that determines how elastic a body is. Glass is far more elastic than rubber in this sense of the word, for although it cannot be bent or distorted nearly so much, it returns much more promptly to its original shape. Ivory and steel are also very elastic.

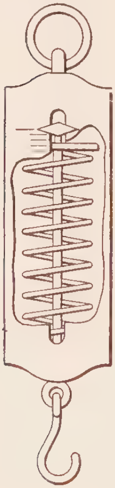

FIG. 5. Spring Balance

A steel spring is almost perfectly elastic, if it is not pulled out too much. Advantage is taken of this fact in making spring balances (Fig. 5). If too great a pull is given a spring it takes a permanent set; in other words, the *elastic limit* of the spring has been exceeded. The *elastic limit* is the maximum force that can be applied to a body, without producing a permanent change in its volume or form.

If a heavy weight is hung from the end of a wire (Fig. 6*a*), the wire *stretches* until the downward pull of the weight is just balanced by the upward pull, or the elastic restoring force of the wire. If the wire is not stretched beyond its elastic limit, it is found that the stretch produced is proportional to force applied,—as discovered by Robert Hooke in 1676. The opposite of stretching is *compression*. For example, when a building is supported on pillars, they are compressed by the weight of the building. The *bending* of a beam is illustrated by figure 6*b*, where the amount of bending is measured by the sag of the middle, as indicated by the scale. The bending is found to be proportional to the force applied, if it is not too great. The *twisting* of a wire or rod can be studied by the method illustrated in figure 6*c*. The twist is produced by

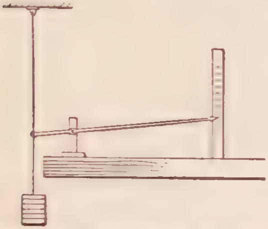

FIG. 6*a*. Elasticity of Stretching

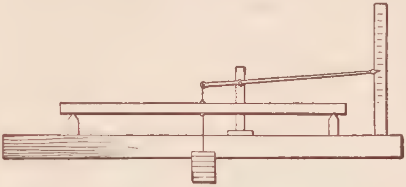

FIG. 6*b*. Elasticity of Bending

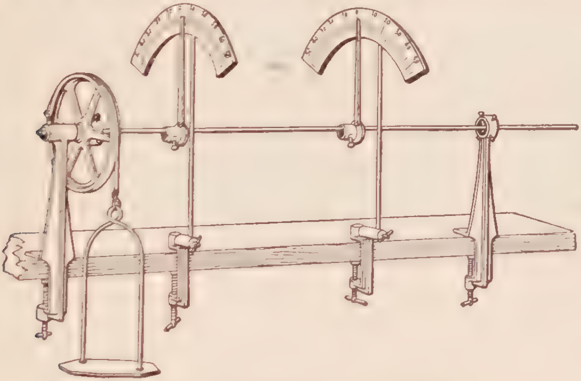

FIG. 6*c*. Elasticity of Twisting

putting weights on the scale pan, and the twist of any length of the rod can be found by means of the circular scale.

In all of these cases forces applied in some way produce distortions of some kind. The word *stress* is used as a general term for the forces, and the word *strain* for the distortions. With these terms we can state the fundamental law of elasticity, called *Hooke's law,* in the form: **Stress is proportional to strain,** if the elastic limit is not exceeded.

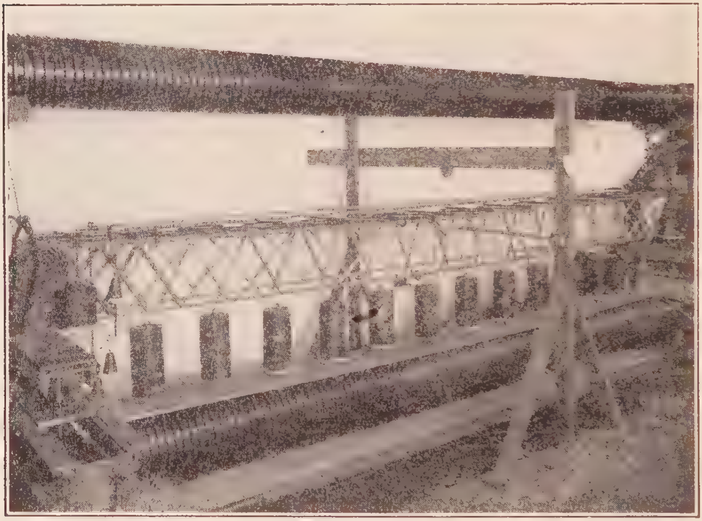

Fig. 7. Testing an airship member for bending, twisting, and extension

Define elasticity. Why is rubber not the most elastic substance you know? Name several elastic substances. If a coiled spring of steel is pulled too far, what happens? Define elastic limit. If you do not exceed the elastic limit, what relation exists between the force pulling a steel wire and the amount it stretches? Distinguish between stress and strain. State Hooke's Law. Express the law of elasticity in terms of stress and strain.

19. Tenacity.—It is more difficult to pull a steel wire apart than a cotton string of the same size. We call this resistance to being pulled apart the *tenacity* of a body. It is measured by pulling on a rod of known size until it breaks, and measuring the pull required. Knowing the size of the rod, and the pull required to break it, we can compute the pull required to break a rod one square inch in cross section. This is called the *tensile strength* of the substance. A table of a few tensile strengths is given below.

Material	*Tensile strength in lbs. per sq. in.*
Brass, cast	18,000
Brass, wire	49,000
Bronze	60,000
Copper, wire	60,000
Gold, cast	20,000
Iron, cast	30,000
Lead, cast	2,800
Platinum, wire	56,000
Silver, cast	40,000
Steel, tungsten	161,000
Tin	5,000
Zinc	7,500

The above are average values and change somewhat with changes in composition.

A knowledge of the tensile strength of materials is often necessary, as in building bridges and engines. Telephone wires are of heavy copper. If the poles on which they are strung are too far apart, the weight of the copper will pull the wires apart, as their tensile strength is not great enough to resist the stress. Hence we must know the tensile strength of copper.

Define tenacity. Define tensile strength. Why is a knowledge of the tensile strength of a substance important?

20. Ductility.—Some metals, such as gold, silver, and copper, are easily drawn into wires. This property of matter which allows it to be drawn into wires is called *ductility*. Wires are drawn by pulling a rod through a cone-shaped hole in a hardened steel plate. This hole is somewhat smaller than the rod. By repeating this process, each time through a smaller hole,

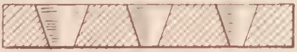

FIG. 8. Draw Plate

the rod is reduced to the desired size. A draw plate of a wire-drawing machine is shown in figure 8. Platinum is the most ductile of all metals; a wire only 0.00003 of an inch in diameter has been drawn from a rod of platinum.

Many substances are ductile only when hot. Glass, when heated red hot, can be drawn into threads so fine that they can be woven into a glass cloth. Even metals are usually much more ductile when hot.

Define ductility. What use is made of ductility? What effect does heat have upon the ductility of a substance?

21. Malleability.—Certain metals, such as gold, may be beaten into thin sheets. The property of a substance which allows it to be beaten or rolled into thin sheets is called *malleability*. Gold, placed between sheets of goldbeater's skin, may be beaten out so thin that fifty sheets would not be so thick as the paper on which this is printed. These sheets of gold are so thin that some light will pass through them, and they appear green when held between the eye and a bright light. This fact enables us to distinguish between real gold leaf and the imitation, called Dutch metal, for the latter does not show the characteristic green color of gold. Most metals are malleable and can be rolled into thin sheets. Iron, copper, brass, and aluminum are common examples.

Define malleability. Why is it a useful property of substances? What class of substances is most malleable?

22. Hardness and Brittleness.—Your thumb nail will scratch a lump of putty. A knife blade will scratch your nail, and a diamond will scratch the knife blade. *Hardness* is the resistance which a body offers to being scratched by other bodies. The putty is very soft, your thumbnail is harder, the knife blade is still harder, and the diamond is the hardest substance known. This is the test of hardness used in the study of minerals. Engineers test hardness by finding how deep a dent a steel sphere of a given size will make when pressed against the substance with a specified force.

Brittleness is the tendency of a body to break when struck. It must be carefully distinguished from hardness. A diamond is very hard, and it is also very brittle. A diamond dropped on a stone floor may break into fragments, yet each fragment will scratch the stone. Glass is not so hard as the diamond, but it is more brittle.

Define hardness. Distinguish between hardness and brittleness. If a body falls to the floor and breaks into many pieces, does it prove that it was not hard? Explain.

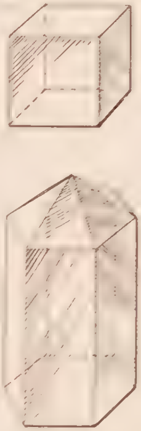

Fig. 9. Crystals of Salt (upper) and of Quartz (lower)

23. Crystalline Form.— Many substances, in separating from liquids in which they are dissolved (§ 34), form regular geometrical solids called *crystals* (Fig. 9). Different solids have different crystalline forms, depending on the forms of the molecules and the forces between them, and it is often possible to identify a substance by examining its crystals. Water forms minute six-sided crystals. A piece of ice or a snowflake is in reality a multitude of such crystals. If you examine a number of fresh, dry snowflakes with a magnifying glass, you will find that all are six-sided in pattern (Fig. 10), though the individual crystals in the snowflake may be too small to be seen separately.

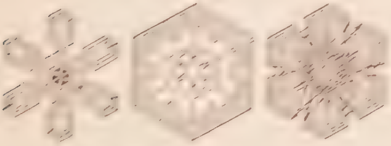

Fig. 10. Snow Crystals

What is a crystal? How may crystals be made? Do all solids have the same shaped crystals? What shape are crystals of snow?

24. Surface Tension.—The molecules in a liquid have a slight attraction for each other. Most of the molecules in a liquid are pulled equally in all directions by the molecules around them. The molecules on the surface, however, are in a different state, because they have no molecules above them to exert a pull (Fig. 11), but are pulled only sideways and downwards. As a result the free surface of a liquid acts as a film which tends to contract, somewhat like a thin rubber sheet stretched tightly over the surface of the liquid.

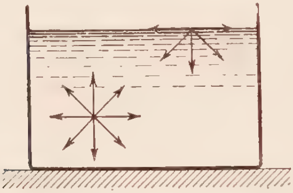

Fig. 11. Surface Tension

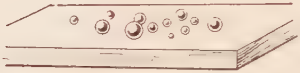

Fig. 12. Surface Tension

Blow a soap bubble on a pipe, and leave the end of the pipe open. The bubble will grow smaller because of the contraction of its free surface. The surface is trying to become as small as possible. Since a sphere has the smallest possible surface for a given volume, small drops of liquid always tend to become spherical. Splash a small quantity of mercury (quicksilver) on a glass plate (Fig. 12). Each little drop of mercury will be nearly spherical. A needle laid carefully on water will float because of surface tension (Fig. 13). The film of water under the needle is depressed and the needle floats in the hollow. A drop of water at the end of a tube (Fig. 14) is held in a little elastic sack, formed by the surface tension.

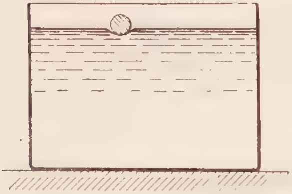

Fig. 13. Needle on Water

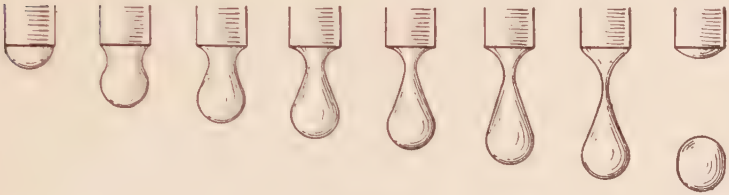

FIG. 14.

The drop falls when gravity becomes too great for the surface tension to withstand.

Prove that the molecules of a liquid attract each other. How do the molecules on the surface differ from those underneath? What is the result of this difference? Define surface tension. Give examples.

25. Capillarity.—If a small, clean glass tube be placed vertically in a beaker of water, the water will rise in the tube to a height greater than that of the water in the beaker. The surface of the water in the tube will be concave. When a similar tube is placed in mercury, the level of the mercury in the tube is depressed below that of the mercury in the beaker, and the surface of the mercury in the tube is convex (Fig. 15). Note that the water wets the glass, while mercury does not. If a number of glass tubes of different diameters be placed in water, it will be seen that the smaller the tube the greater the elevation of the water (Fig. 16). This elevation or depression of liquids in fine tubes is called *capillarity*. Oil rises in the wick of a lamp and blotting paper absorbs ink, because of capillary attraction. Place two glass plates

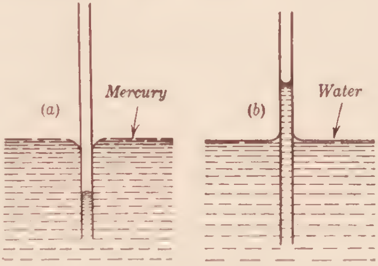

FIG. 15. Capillary Action of Water and Mercury in Small Tubes

(Fig. 17) in contact at one edge, keeping the other edges separated a small distance, and stand them in water. The water will be drawn up between the plates so as to form a curve that is highest where the glass plates are closest together.

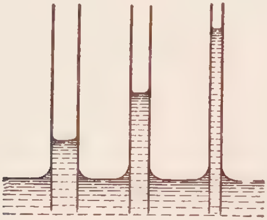

FIG. 16. Capillary Action Varies with Diameter of Tube

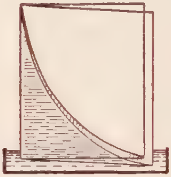

FIG. 17. Capillary Action

From the above facts we may conclude that:

Liquids ascend in small tubes when they wet them, and the surface of the liquid is concave.

Liquids are depressed in small tubes when they do not wet them, and the surface of the liquid is convex.

The amount of elevation or depression is inversely proportional to the inside diameter of the tube.

If a small tube is placed in a glass of water, why will the water not stand at the same height in the glass and in the tube? If tubes of different sizes are used how does the height of the water compare in them? Why do these same results not occur if mercury is in the glass tube? State the three laws of capillarity.

26. Soil Capillarity.—The farmer derives great benefit from an understanding of capillarity. When it rains, the water sinks into the soil. The small particles of the soil pack closely enough together to leave minute spaces, and these have a tendency to lift the water by capillary action. Thus the rain water in the soil is drawn to the surface and evaporates, leaving the ground dry and the plants thirsty. To prevent this, the farmer stirs the surface of the ground (cultivates the soil), as soon as the surface is dry after a rain. This breaks up the small crevices, thus diminishing the capillary action, and the water stays in the ground where it is needed. Thus crops can be raised where the rainfall is slight (dry farming). This method is used in the arid regions of the West (Fig. 18).

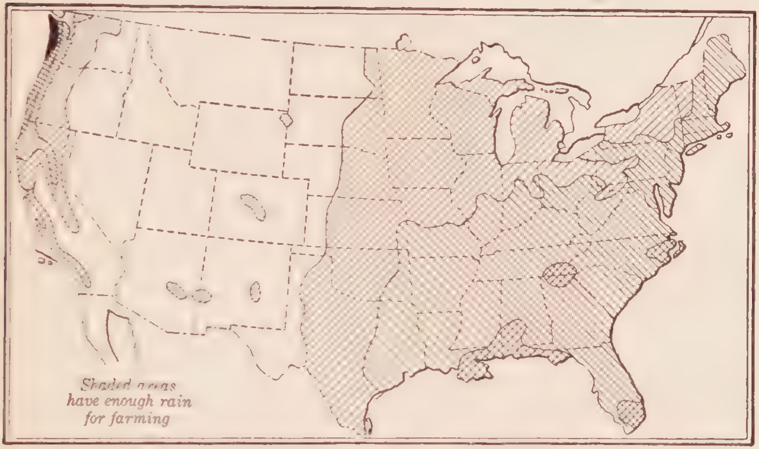

FIG. 18.

How is capillarity in the soil important? Why does the farmer cultivate his corn field after a rain? What is dry farming? Where is it practised?

27. Porosity.—A piece of pumice stone placed on water floats, but in a short time water enters the pores of the pumice and it sinks. Pumice is porous, that is, there are small passages throughout the mass of the stone. This can be shown by powdering the pumice and compressing the powder. Its volume will then be much less than the original volume of the pumice. For the same reason, floating wood becomes water-logged and sinks. Even such hard stones as agate are somewhat porous. Polished black-banded agate is often colored artificially by soaking the stone in syrup, and then heating it. The stone absorbs some of the syrup, which chars on heating, and the stone therefore turns black.

What is a porous substance? A log floats for a time but finally sinks. Why? Mention examples of porosity.

28. Mobility and Viscosity.—Liquids differ greatly in *mobility,* or the readiness with which they yield to any force that tends to cause a flow. Gasoline is very *mobile,* while pitch has little mobility. Gases are much more mobile than liquids.

Both liquids and gases possess *viscosity,* that is, the frictional resistance a fluid offers to flowing when set in motion. Rainwater runs rapidly down an inclined roof or through a vertical pipe, because its viscosity is small compared with the force of gravity. Water is of little use as a lubricant, because it would be squeezed too quickly from between two surfaces that are pressed together. For this purpose an oil, of greater viscosity than water, is needed. The viscosities of liquids can be compared by seeing how quickly they will run out of a funnel with a long, fine stem. Gases are much less *viscous* than liquids, and hot liquids are less viscous than cold.

Define mobility. Which are more mobile, gases or liquids? Illustrate. Are all liquids equally mobile? Illustrate. Define viscosity. Which are more viscous, liquids or gases? Illustrate. What effect does heating a substance have on its viscosity?

EXERCISES

1. Mention some important examples of cohesion and some of adhesion. Give reasons for your statements.

2. Explain the difference between tenacity, ductility, and malleability. Give illustrations of the use of each.

3. Is coal hard or brittle, or both? Is glass? Is copper?

4. What is a a crystal? Name two common substances having crystals the form of which can be easily seen.

5. What is the cause of surface tension? Give several illustrations. Why are rain drops nearly spherical?

6. What is capillarity? What causes it? Give six illustrations and explain each of them.

7. The bearings of an automobile are often so tight that it is difficult to turn the engine. How can oil get into these bearings to lubricate them?

8. What is elasticity? How could you prove that glass is very elastic?

9. State Hooke's law of elasticity.

10. What is porosity? Give four different useful instances.

11. What is mobility, as applied to fluids? Name some mobile liquids.

12. What is meant by viscosity? Give examples.

13. How could you find which of two oils is the more viscous?

CHAPTER IV

MOLECULAR MOTIONS

29. Motion of Molecules.—While molecules are too small to be seen separately, even with the most powerful microscopes, many of the properties of liquids and gases show that their molecules are in a state of perpetual agitation, dashing to and fro, hitting one another, and moving from place to place. The nature of the motion can be illustrated by heating a glass tube from which the air has been removed, and which contains some mercury and a large number of small pieces of glass (Fig. 19). The particles of glass are carried up into the tube by the stream of mercury molecules that rise from the boiling mercury, and there they dash around violently, striking each other and the sides of the tube. . . . These glass particles are, of course, much larger than molecules, but the way in which they act shows us how the invisible molecules of a gas behave.

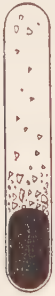

FIG. 19. Motion of Molecules Illustrated

The velocities of molecular motions have been determined, but we shall not try to describe the methods here. The molecules of hydrogen have the immense velocity of 1700 meters per second, or more than a mile a second. Heavier gas molecules move more slowly, but even they have a very high velocity.

Are the molecules of liquids and gases at rest or in motion? Give proof. Why is their motion zigzag? Is the motion faster in light gases or in heavy gases?

30. The Three States of Matter.—There are three *states* or conditions in which we know matter. Water is familiar to us in all three states. We have solid water called *ice,* liquid water called simply *water,* and a gas called *steam* or water vapor.

A solid placed in a vessel retains its own size and shape. A liquid takes the shape of the vessel, but retains its own size. A gas takes both the size and shape of the vessel in which it is placed.

A **solid** has a definite size and a definite shape.

A **liquid** has a definite size, but no definite shape.

A **gas** has neither a definite size nor a definite shape.

These three states depend upon the freedom of the molecules to move about. In a solid the molecular motion is limited, in a liquid the molecules move about more freely, in a gas they fly about with tremendous speed.

It is sometimes difficult to say whether a substance is a solid or not. A lump of pitch seems to be solid, yet, when placed in a bowl, it will slowly take the shape of the bowl. This shows that it is really a very viscous liquid. A thin jelly quivers and seems more liquid than pitch, yet it does not take the shape of a vessel in which it is placed, and it is therefore a real solid.

In how many states can matter exist? Can the same substance exist in all three states? Illustrate. In which state do the molecules have the greatest freedom of movement? In which state do they have the least? Define solid, liquid, and gas.

31. Diffusion of Gases.—Chlorine is a heavy, greenish-yellow gas, with a very irritating odor. If a little be placed in the bottom of a cylinder filled with air, the chlorine will gradually mix with the air, until it is equally distributed throughout the whole volume of the air, and this in spite of the fact that chlorine is more than twice as heavy as air.

Hydrogen is the lightest gas known, weighing about 1/14th as much as air. Yet if a bottle filled with hydrogen be placed, mouth downward, close to the ceiling of a room, the hydrogen will leave the bottle and mix uniformly with the air in the room. Such spontaneous mixing of gases always occurs when gases are brought into contact, no matter what may be their difference in density. This process is called *diffusion*. It is very important to us, since, without it, the atmosphere around us would be arranged in layers, the heaviest gas at the bottom.

Gases diffuse readily through porous solids, such as flower pots, bricks, and battery cups. Light gases diffuse more rapidly than heavier ones. For example, let a glass jar that is filled with hydrogen, the lightest gas known, be lowered over a battery cup, which is fitted with a cork (Fig. 20). If a long glass tube passes through the cork and dips under water, the hydrogen will pass inward through the porous wall of the cup so much faster than the air will pass outward, that air will bubble from the end of the tube and rise through the water. Illuminating gas may be used instead of hydrogen.

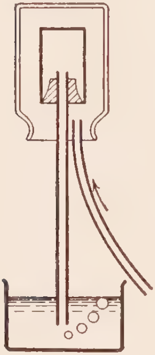

FIG. 20. Diffusion of Gases

If a heavy gas is put below a light one in a vessel, will they remain apart? Explain. Define diffusion. Will porous solids keep gases apart? Describe an experiment to prove your answer. How is diffusion of gases important to us?

32. Diffusion in Liquids.—Liquids, as well as gases, are composed of molecules that are not in contact and are in rapid motion. If two liquids, soluble in each other, be brought into contact, they will diffuse just as gases will, but more slowly. This is easily shown by placing bromine, a very heavy, dark red liquid, in the bottom of a jar, and filling the rest of the jar with water. The water will gradually become colored because the bromine will diffuse through it.

Will some liquids diffuse as do gases? Illustrate. Will all liquids so diffuse? Mention two which will.

33. Diffusion in Solids.—The molecules of solids move much less freely than do those of gases and liquids. Diffusion in solids is therefore slow and difficult to observe, but it does occur. If a disk of gold is pressed against a disk of lead, and the lead examined after a long time, it will be found to contain gold which has diffused into the lead. The lead will also diffuse into the gold. The results of such experiments show that even in a solid, molecules have some liberty to wander around.

Prove that diffusion exists in solids. How does it compare in speed with diffusion in liquids and gases? Mention two solids which will diffuse when in contact.

34. Solution.—When solid copper sulphate (blue vitriol) is placed in water, it mixes with the water and slowly disappears, coloring the water a bright blue. Molecules leave the solid and diffuse into the liquid. We call the resulting liquid a *solution*. If we add more and more copper sulphate, a time finally comes when the water can dissolve no more, and the solution is then *saturated*. If we heat the water, it dissolves more of the copper sulphate, but again there comes a time when it can dissolve no more. If the hot saturated solution be cooled, the excess copper sulphate will become solid, appearing in the form of crystals (§ 23). Solids are generally more soluble in hot than in cold liquids, but there are exceptions to the rule. Cooks often speak of *melting* sugar in water. This is, of course, an error; they should say *dissolving* sugar in water.

Many substances that we consider insoluble dissolve slightly in water. In making delicate chemical analyses, it is necessary to take into account the glass dissolved by the liquids used. Even rocks are somewhat soluble in water.

Define solution. When is a solution saturated? Are solids usually more soluble in hot or in cold water? Are all solids soluble in water? Illustrate.

EXERCISES

1. What is the cause of diffusion? The result?

2. How could you demonstrate diffusion?

3. Mention some circumstances that help diffusion in the air.

4. Mention some important instances of diffusion.

5. What is a solution? A saturated solution?

6. Do solids dissolve in liquids? Do gases? Give examples.

7. Why is sea water salt and lake water fresh?

8. Why does rain water seem tasteless?

9. What are the three "states of matter"? How do they differ?

10. Account for the fact that the constitution of the atmosphere is everywhere about the same near the earth's surface.

CHAPTER V

FLUIDS

LIQUIDS AT REST

35. Fluids.—Liquids and gases agree in one property. They can flow, and they are therefore classified together as fluids. Water readily flows down a channel forming a river, and air flowing over land is a wind. But liquids and gases differ in other important respects. One difference, that of expansion to fill a vessel, has already been stated (§ 30). Another is as regards resistance to compression. A gas in a cylinder can be readily compressed by pushing in a piston. A gas is a very compressible fluid. But when the same experiment is tried with water in a cylinder, the decrease in volume is very small. When the force exerted on the piston is doubled, the compression of the water is only 1/20,000 of the original volume. With ether it is somewhat greater, but with mercury it is much less. In all cases it is very small, and a liquid may usually be regarded as an incompressible fluid. The molecules of a liquid are already so close together that pushing them still closer is difficult.

What is a fluid? Are liquids fluids? Are gases fluids? Distinguish between liquids and gases. Which are more compressible, gases or liquids? Why will even a small amount of a gas fill any vessel in which it is put? Why will a liquid not do so?

36. Liquid Pressure.—Imagine that we have a box that measures just one foot cube on the inside (Fig. 21). Fill this box with water. The water will weigh about 62.5 pounds.

This weight will press on the bottom of the box, just as if we placed a weight of 62.5 pounds in the box. If we drill a hole in the bottom of the box, this pressure will force the water out through the hole.

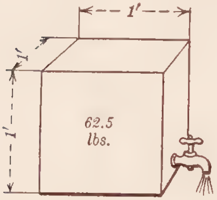

Fig. 21. Liquid Pressure

If we use another box, one square foot in cross section, but 10 feet high, it will take ten times as much water to fill it (Fig. 22). This water will weigh 10 times as much, or, 625 pounds. The pressure on the bottom of this box will be 10 times as great, or, 625 pounds per square foot. **The downward pressure is proportional to the depth of the liquid.** To find the total force exerted on the bottom of a tank, we must find the area of the bottom in square feet, multiply this by the height of the water in feet, and this by 62.5 pounds.

If the tank be filled, not with water, but with some other liquid, we can obtain the pressure on the bottom by the same process, but using, instead of 62.5 lb., the weight of one cu. ft. of the liquid. Glycerin weighs 78.5 lb. per cu. ft. In a rectangular tank 3 ft. x 6 ft. and 8 ft. high, filled with glycerin, the total force on the bottom would be 3 × 6 × 8 × 78.5 = 11,304 lb. The *pressure* per sq. ft. would be 8 × 78.5 = 628 lb. Thus *the pressure is proportional to the density of the liquid.*

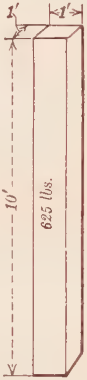

Fig. 22. Liquid Pressure

The word pressure, in this connection, always means *force per unit area.* In the preceding we have used the square foot as unit of area, but the square inch is often used. Pressure per square inch is equal to pressure per square foot divided by 144.

Why will a liquid exert a pressure on the bottom of a box which contains it? What determines how great this pressure will be? What will determine the total force exerted by the water? How will you find the total force on the bottom of a tank filled with water? Why do all liquids not produce the same pressure? Distinguish between the terms pressure and total force.

37. Water Seeks Its Level.—If we connect a pipe with a hole in the bottom of a box that is filled with water (Fig. 23), the pressure of the water in the box will force the water up the pipe, until it is balanced by the downward pressure of the water in the pipe. This occurs when the level of the water is the same in box and pipe. The shape or size of the pipe has no influence on the result. The level of the free surface is everywhere the same, or "water seeks its level."

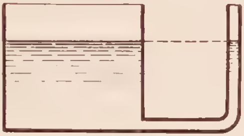

FIG. 23. Water Seeks Its Level

This is the principle used in distributing water to all parts of a city. If the source of water supply is at a higher level than the city, it is only necessary to build a reservoir. The water fills it, and the pressure on the bottom of the reservoir due to the height, or *head* as it is called, of the water, forces the water through the pipes into the houses. If the reservoir is not high enough to give sufficient pressure, it is necessary to pump the water into a reservoir or standpipe, located at a sufficient elevation to give the necessary pressure or head (Fig. 24).

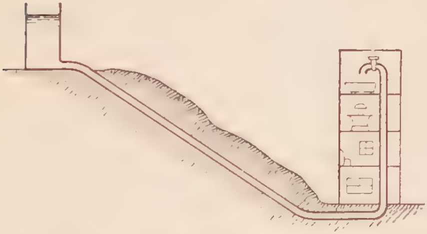

FIG. 24. City Water Supply System

The city water pressure is often not sufficient to force water to the top of high buildings. The Woolworth building in New York City is 790 feet high. The city water pressure is not sufficient to force water to the upper stories. By placing a tank on the roof of such a building, and pumping water into it, a constant supply of water for the building is provided. The pressure at any faucet can be easily found. If the surface of the water in the tank is 800 feet above the lowest faucet, there will be at that faucet a pressure of $800 \times 62.5 = 50{,}000$ lb. per sq. ft., or 347 lb. per sq. in. In a similar way the pressure at any other point can be found.

How does the level of a liquid compare in different connecting vessels? What effect does the relative size or shape of the vessels have? Of what importance is this behavior of liquids? What is the purpose of a standpipe in a city water system? When the city water pressure is insufficient how are high buildings supplied with water? Is the pressure in the pipes of a tall building the same on all floors? How would you find the pressure at any height?

38. Driven Wells.—When rain falls, the water sinks into the ground until it reaches an impervious layer of rock or clay, and there it accumulates. The level of the top of this *ground water* is called the *water table.* Sometimes this water table rises to the surface, and this results in a spring or lake; sometimes it is hundreds of feet below the surface (Fig. 25). The top of this water table is not horizontal, because the water is always draining down from the higher levels.

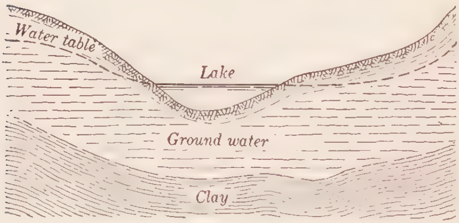

Fig. 25. The Course of Lakes and Springs

Often the ground water is caught between two layers of clay (Fig. 26). If an iron tube be driven into the ground, at a point such as *A*, until it penetrates the upper of these two layers, the confined water will rise through the pipe, because it will "seek its level." Such a well is called an *artesian well.*

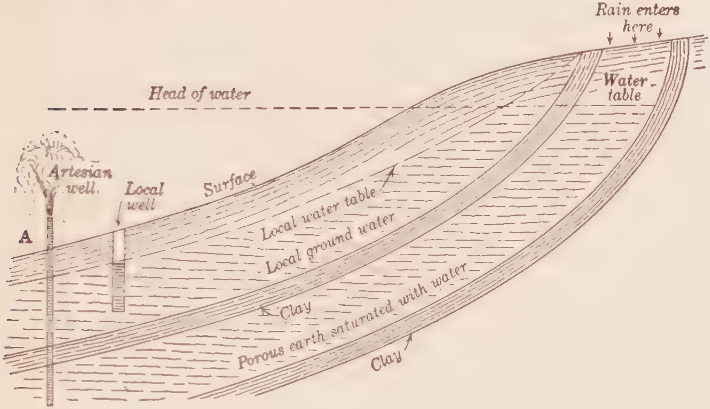

Fig. 26. Artesian Wells

They are common in the western part of the United States. Sometimes it is necessary to drill to a depth of 3,000 feet or more, before water is found in sufficient quantity.

What becomes of much of the rain which falls? What name is given to this water? What is the water table? Is it always level? What is an artesian well? What conditions make an artesian well possible? Why does the water sometimes come to the surface without pumping?

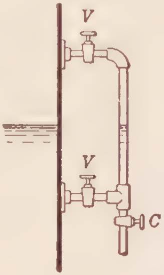

Fig. 27. Gauge Glass for Boilers

39. Gauge Glasses.—A common example of the fact that “‘water seeks its own level” is the gauge glass on a boiler. The engineer needs to know the level of the water in his boiler, in order to avoid an explosion. This is provided for by the gauge glass on the side of the boiler (Fig. 27). The water level in the glass is the same as that in the boiler. Valves *V* allow the pipe leading into the boiler to be closed if the glass should break, and a cock C allows the water to be drawn from the gauge for cleaning and testing.

What is a gauge glass on a boiler? Describe such a gauge glass. What purpose does it serve?

40. Pascal's Principle.—Once more think of our one-foot-cube box, filled with water. The water has no motion. Consider some particular water particle. Since it stays where it is, it must be pressed equally in all directions, for if this were not so, it would move until the pressure became equal on all sides of it. Evidently then, **the pressure at any point in the water must be the same in all directions.**

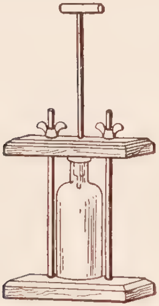

FIG. 28. Breaking a Bottle by Water Pressure

If a bottle is filled with water and closed by a perforated cork, through which a rod passes, when the rod is pressed into the bottle the pressure on the water is increased until at last the bottle breaks (Fig. 28). Since the water particles are not set in motion, it is evident that the *pressure is transmitted undiminished in all directions*, throughout the water. These facts are summed up in Pascal's principle.

Pressure applied to an inclosed fluid is transmitted equally and undiminished in all directions to every part of the fluid.

In this discussion water has been used as the illustration, since everyone is familiar with it, but the same statements would, of course, be true of any fluid.

In a vessel of water how does the pressure to the right at any point compare with the pressure to the left? How do you know? State Pascal's principle. Does Pascal's principle hold good for any fluid?

41. The Hydrostatic Bellows.—If a collapsible bellows, provided with an open side tube (Fig. 29), be filled with water, and a boy steps on it, you would naturally think that water would be forced out of the open side tube, producing a fountain. As a matter of fact, only a small amount of water is forced into the tube. It rises from *A* to some point *B* and then stops. This illustrates Pascal's law. If the upper disk of the bellows has an area of 1,000 square inches and the pipe an area of one square inch, then one pound of water in the tube (a height of about two feet) will support a weight of one pound per square inch, or 1,000 pounds in all, on the top of the bellows.

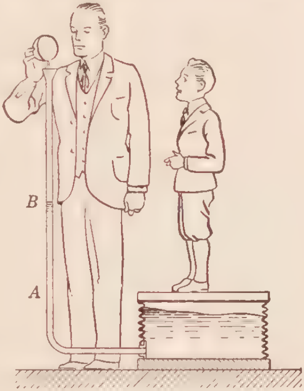

FIG. 29. Hydrostatic Bellows

How can the small amount of water in the pipe (Fig. 29) support the weight of the boy? How high would the water have to stand above *A* in the figure in order to support your weight?

42. Hydraulic Press.—Pascal's principle is made use of industrially in the *hydraulic press.* This is a machine that makes it possible to exert an enormous force with very little effort. Imagine a box of the shape shown in cross section in figure 30. The cross-sectional area of the small piston *A* is one square inch. The cross-sectional area of the large piston *B* is 100 square inches. If we push down on the small piston with a force of one pound, each square inch of

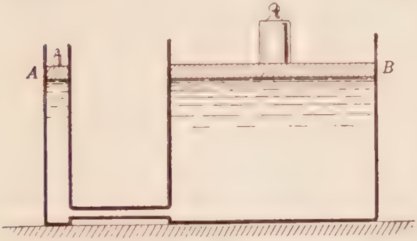

FIG. 30. Model Hydraulic Press

the large piston will be pushed up with a force of one pound. Since the large piston has an area of 100 sq. in., the total upward push will be 100 pounds, that is, a weight of one pound on the small piston will support a weight of 100 pounds on the large piston. The pressure per unit of area is the same throughout the liquid, but, since the large piston has a very large area compared to the small piston, the total force exerted by it is proportionally greater. At first it seems impossible that a pressure of one pound per sq. in. can produce a force of 100 pounds, but we must remember that for every inch the small piston is pushed down, the large piston will rise only 1/100 inch. Thus as we gain in force we lose in distance. We have neither increased nor diminished our store of *energy*. The hydraulic press enables us to exert enormous forces, such

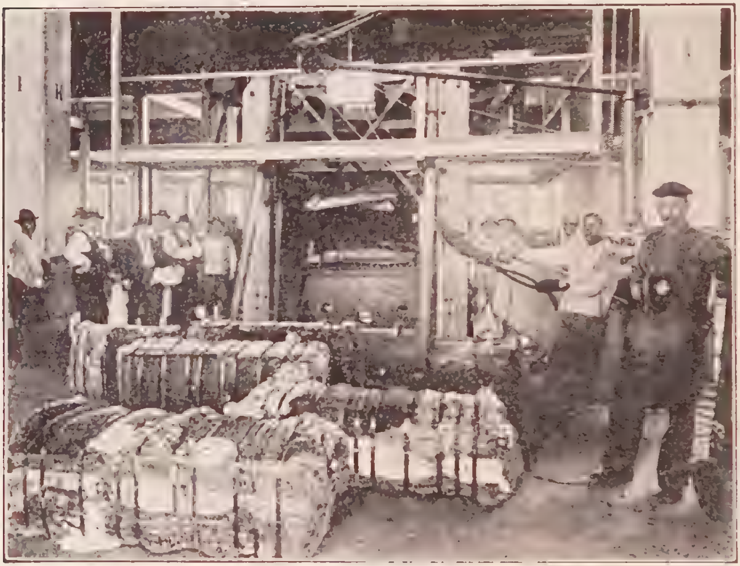

Fig. 31. Cotton Press

as are used in baling cotton and punching steel plates. The liquid used in the press need not be water. Indeed, in practice oil is often used. The principle and operation are the same, whatever liquid is used (Fig. 31).

Describe the hydraulic press. Show how Pascal's principle explains the action of the press. What is the hydraulic press used for? Can any other liquid than water be used in such a press? Explain.

43. Hydraulic Elevators are often used because of their comparative safety. A pit is dug to a depth equal to the height to which the elevator cage is to be raised. In this pit a pipe is placed, having in it a closely fitting plunger (Fig. 32). The elevator cage is firmly fixed on the top of the plunger. The weight of the elevator is almost counterbalanced by a weight *W*, so as to diminish the effort required to raise it. By means of a small pipe, water is admitted to the bottom of the pit. Often the pressure of water from the water main is sufficient to raise the large plunger. If it is not, a pump is used to force the water in. As the pipe is filled, the plunger carrying the elevator cage is raised.

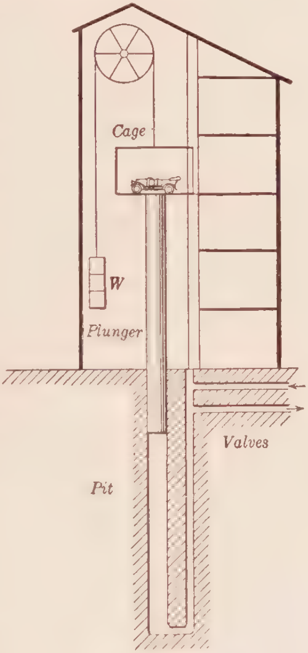

Fig. 32. Hydraulic Elevator

When the elevator attendant moves the control handle, the water valve is opened, thus admitting water to the bottom of the pit, and the plunger, with the elevator cage mounted on it, rises. When he moves the handle back, the valve closes and the elevator remains stationary. To descend, he moves the handle in the opposite direction, which opens a valve in the pit, and the water escapes through the valve. The weight of the elevator then forces it down.

Describe a hydraulic elevator. Explain how the elevator is lifted. How is it made to descend? What is the purpose of the counter weight?

44. Forces on Surfaces of Vessel.—When we fill a box with water, the water exerts pressure, not only on the bottom of the box, but on the sides as well. This side pressure is zero at the surface of the water. At any point it is proportional to the depth of the water, because the weight of the water is proportional to the depth. As the pressure increases regularly from the top to the bottom, we can calculate the whole force by obtaining the average pressure and multiplying this by the area of the side. To obtain the average pressure we divide the height of the water by two. An example will make this clearer. Suppose a box 3 ft. x 4 ft. and 5 ft. high is filled with water and we wish to find the force exerted on each side and on the bottom.

Area of Surface	×	*Average depth*	×	*Density*	= *Force*
(1) Short side (3 × 5)	×	5/2	×	62.5	= 2343.75
(2) Long side (4 × 5)	×	5/2	×	62.5	= 3125
(3) Bottom (3 × 4)	×	5	×	62.5	= 3750

Where else does water in a box exert pressure except on the bottom? How does the pressure on the side near the bottom compare with the side pressure near the top? How can you find the average pressure on the side? How can you compute the total force on the side?

45. Pressure Is Independent of the Shape of the Vessel.—To illustrate this, the apparatus shown in figure 33 may be used. When water is poured into the funnel, the water will come to the same level in all of the tubes, showing that the pressure on the bottom must be the same, irrespective of the shape of the vessel. If this were not true, the height of the water in the different tubes would vary.

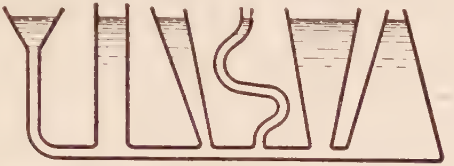

FIG. 33. Pressure Exerted Is Independent of Shape of Vessel

Do the pressures on the bottom and on the sides depend on the shape of the vessel? How do you know this?

46. Force Exerted on Any Immersed Surface.—If the surface is not horizontal, but inclined, the pressure on it increases from top to bottom. If the inclined surface is of regular shape, such as a rectangle, the average pressure on it is the pressure at its center. In this case the force exerted on the surface is equal to the weight of a column of liquid, having a base equal to the area pressed on, and a height equal to the depth of the center of area below the surface of the liquid. (For an irregular surface the average pressure is the pressure at the center of gravity of the surface.)

Force exerted = area × depth of geometrical center of immersed surface × density of liquid.

State the general rule for finding the force exerted on any immersed surface.

47. Dams.—A dam is always thicker at the bottom than at the top (Fig. 34), because of the greater pressure it must resist at the bottom. To compute the force exerted on the side of a dam, we must use the method given in the preceding paragraph. Suppose that in figure 34 the depth of the water is 10 feet, and that, owing to the shape of the bed of the stream, the geometrical center of the dam is 4 feet below the surface of the water, while its area is 250 sq. ft. The total force exerted on it will be 250 × 4 × 62.5 = 62,500 pounds. Notice that this force is not dependent on the length of the lake held in by the dam, so long as the water is not in motion. If the lake is large, and a stiff wind is blowing, so that long waves are produced, this force may be greatly increased. If water is flowing over the dam, the force will also be greater than that computed.

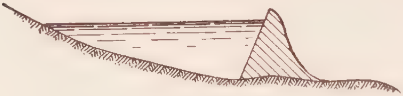

FIG. 34. Cross Section of Dam

For safety under all possible conditions, a dam is usually built so as to be much stronger than would be necessary to resist the calculated force. In the above case the total force possible from all causes might amount to 100,000 pounds. The dam might then be built to resist a force of 300,000 pounds. The ratio between the strength of the dam and the total force that the dam would probably be called upon to resist is called its *factor of safety*. In the above case it would be three. In building bridges, roofs, and all structures and machines, it is necessary to provide a factor of safety. It varies from 3 to 8, depending on the conditions to be met.

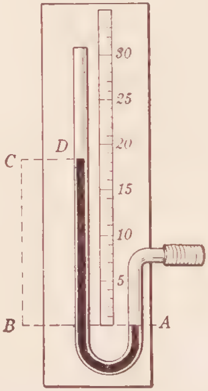

FIG. 35. Pressure Gauge

Why are dams thicker at the bottom than at the top? Does the pressure of the water on the dam depend on the size of the lake behind the dam? Explain. What is meant by the term factor of safety?

48. Pressure Gauges.—To measure water pressure, we use a pressure gauge. The simplest form is an open mercury manometer (Fig. 35). This consists of a U-shaped tube, with mercury in the bend. When one side is connected to water under pressure, as in a faucet, the pressure of the water forces the mercury up the tube. As mercury is 13.6 times as heavy as water, a head of water of 13.6 inches will force the mercury up one inch. By placing a scale back of the tube, the difference in level of the two arms can be read, and this multiplied by 13.6 gives the head of water.

The mercury gauge is simple and accurate, but it is easily broken and not very portable. In practice we therefore generally use a Bourdon gauge. This is a metal tube, elliptical in cross section, and bent into a ring form (Fig.36). One end of the tube is closed and free to move. The other end is open and fixed to the frame of the gauge. When the open, fixed end of the tube is connected with a water pipe, the water pressure tends to straighten the tube, thus moving the closed or free end. The greater the pressure, the greater the movement. This free end of the tube is connected with a pointer, which moves over a dial. By placing the gauge on pipes in which known pressures are maintained, and then marking the dial, we graduate the gauge. Such gauges are usually marked to read in pounds per square inch. Steam boiler gauges are of this type.

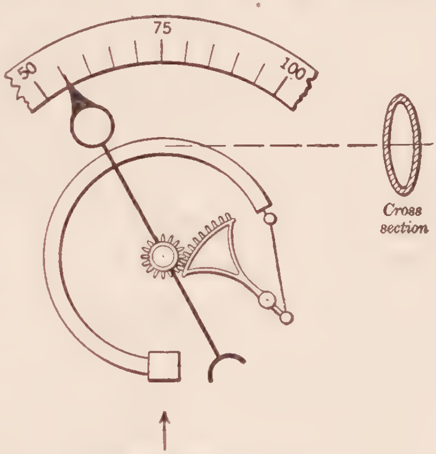

Fig. 36. Bourdon Gauge

What is a pressure gauge? Describe a manometer. What is a Bourdon gauge? Why is it better than a mercury gauge? Describe a Bourdon gauge. How does it operate? Which kind of gauge is usually used on a steam boiler?

49. Pressure in Water Pipes.—The pressure in a system of water piping is least at the top of the house and increases as we go down, because it depends on the height of the reservoir above the faucet. The water pressure also depends on the amount of water that is being drawn from the pipes. If the water pressure is low, and water is being drawn from the lower floors of the house, it may not run at all from the upper faucets. This can be easily shown by the apparatus pictured in figure 37. As long as the end *A* is closed, water will stand at the same level in all of the pipes, *B*, *C*, *D*, *E*, but when the end *A* is opened, the water levels will fall to the positions shown. To insure a sufficient supply to all parts of a house the water pipes should be large.

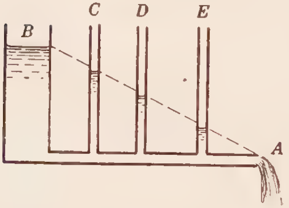

FIG. 37. Pressure in Water Pipes

Prove that the water pressure is not the same at all faucets in a tall house when all are closed. What effect does opening a faucet at the bottom of the house have on the pressure at all the other faucets? How may this effect be made as small as possible?

EXERCISES

1. State the points of difference between a liquid and a gas. Between a fluid and a solid.

2. Why is a dam thicker at the bottom than at the top?

3. State the law of liquid pressure. Upon what does the pressure upon any given surface depend?

4. Why do they not make reservoirs high enough to supply the upper floors of the highest buildings in some large cities?

5. What influence has the shape of a vessel upon the pressure on a given sq. ft. of the bottom?

6. Why is it that the dikes which keep the North Sea from flooding Holland need to be only a few feet thick?

7. What is the purpose of the "stand pipe" in the city water supply system?

8. How do you explain the operation of a gauge glass?

9. Explain the carpenter's level.

10. Why does water "seek its level"? What use have we made of this principle?

11. Why are roads "crowned"?

12. What is a "water break"?

13. State Pascal's law.

14. Explain the operation of an artesian well. How does it differ from an ordinary well?

15. Sketch, describe and explain a hydraulic press. What advantage does it offer? What is a hydraulic jack?

16. Hydraulic elevators are the most expensive to install. Why are they used? What principle explains their action? What is the advantage of the counterweight?

17. A flat piece of wood or cork, placed in contact with the flat bottom of a tank, will sometimes remain there though the tank is full of water. Explain.

18. Describe a simple experiment to prove that pressure is independent of the shape of the vessel, and of the quantity of water it holds.

19. The Titanic sank in 12,480 feet of water. Why has no effort been made to recover the valuables on board?

20. Can a submarine operate at a depth of 500 feet? Explain.

21. What is meant by the factor of safety? Why is it necessary?

PROBLEMS

1. Gasoline weighs 43 lb. per cu. ft. What is the force exerted on the bottom of a cylindrical tank 12 ft. in diameter, and filled to a height of 24 ft. with gasoline? What is the pressure per sq. ft.? Per sq. in.?

2. What would the force exerted on the bottom in Prob. 1 have been if the tank had been filled with glycerine? One cu. ft. of glycerine weighs 78.5 lb.

3. A swimming pool is 20 x 60 ft., and is filled to a depth of 7 ft.

with water. Find the force exerted on the (a) bottom, (b) short side, (c) long side.

4. At one spot in the South Pacific, the ocean is 30,930 feet deep. What is the pressure in tons per sq. ft. at that point? Assume sea water to weigh 64 lb. per cu. ft. What would happen to a corked bottle, filled with sea water, thrown into the ocean at this point?

5. A rivet drops out of the hull of a submarine when it is at a depth of 120 ft., leaving a ¼ in. hole. What force would be required to hold a plug in the hole?

6. The pressure in a New York City water main is 85 lb. per sq. in. The highest faucet in a building on that street is 106 ft. above the water main. Will water run from the faucet? If so, with what force? If not, how high will the water rise?

7. The plunger of a hydraulic elevator has a diameter of 10 inches. The water pressure in the city mains is 60 lb. per sq. in., and the building is 65 ft. high. The elevator with its load weighs 4 tons. Will it be necessary to install a pump, or will the city water pressure lift the elevator? (Disregard losses.)

8. The areas of the two pistons of a hydraulic press are as 4 : 96. A force of 70 lb. is exerted on the smaller piston. What force is exerted on the larger piston? If the smaller piston moves 3 in., how far will the larger piston move?

9. The top of the hydrostatic bellows (Fig. 29) has an area of 4 sq. ft. A boy weighing 120 lb. steps on it. How far will the water be forced up the tube, if the tube has an area of 1 sq. in.?

10. The two pistons of a hydraulic press have diameters of 1 and 10 in. respectively. (a) How do their areas compare? (b) A pressure of 20 lb. per sq. in. is applied to the smaller piston. What force per sq. in. must be applied to the larger piston to hold it stationary? (c) A force of 90 lb. is applied to the smaller piston. What force must be applied to the larger piston to hold it stationary? (d) If the smaller piston moves 8 in., how far will the larger piston move?

CHAPTER VI

BUOYANCY OF LIQUIDS

50. Buoyant Force.—If we place a cork under water, the weight of the cork pulls it down, while the water pushes it up. Since the upward push of the water is greater than the downward pull due to the weight of the cork, the cork comes to the surface and floats. A block of iron used in the same way sinks, because its weight is too great to be sustained by the upward push of the water. The next time you are in swimming, pick up a stone under water, and then lift it out of the water. You will find that stones that you can lift in the water are sometimes too heavy for you to lift when they are out of the water. This will make the upward force of water evident to you. The same thing is, of course, true of our own bodies. When we are in swimming, the upward push of the water enables us to float.

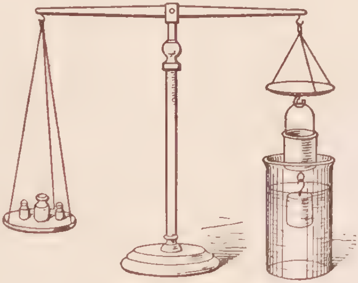

FIG. 38. Archimedes' Principle

It is possible to measure this upward push (buoyant force) of water. Take a cylindrical metal block, and a metal case just large enough to hold the block. Hang both the block and case from the beam of a balance (Fig. 38), and counterbalance them with weights in the other pan of the balance. Now place a glass of water so that the block hangs suspended in it. The balance will show that the water is buoying the block up. To restore the equilibrium we must add more weight to the side from which the block hangs. This we can do by pouring water into the case above the block. When we have filled the case with water, the equilibrium of the balance will be exactly restored, showing that the block was buoyed up with a force *just equal to the weight of its own volume of water.* If we repeat the experiment, using kerosene instead of water, we shall find the same result. The upward push (buoyant force) of the kerosene is just equal to the weight of a quantity of kerosene of the same volume as the block. This force of buoyancy, acting upwards on the body immersed, is sometimes called an apparent loss of weight, though there is, of course, no change in the real weight of the body.

Why is it necessary to hold a cork under water to prevent it from coming to the top? Does a stone feel heavier when it is under water or when it is above water? Explain. Is this upward force of the water of any use to a swimmer? What is this upward force called? Explain how you would measure the buoyant force on a given block.

51. Archimedes' Principle.—The fact proved in the last paragraph may be stated thus: **The apparent loss of weight of a body immersed in a fluid is equal to the weight of the displaced fluid.** This is called **Archimedes' principle,** after the Greek philosopher Archimedes. The story goes that Hiero, king of Syracuse, gave a certain weight of gold to a goldsmith to fashion into a crown. When the crown was made, its weight was the same as that of the gold, but the king suspected that the goldsmith had kept part of the gold and substituted an equal weight of silver. He gave Archimedes the problem of finding if this were so, without destroying the crown. Archimedes puzzled over the problem for a long time, until one day, while in the public bath, he got the clue that he needed, and, rushing from the bath with a shout of

"Eureka! Eureka!" (I have found it), he hurried home to try the test on the crown, which was found to contain silver.

That Archimedes' principle must be true is easily proved in a different way. Imagine a rectangular block 3 x 5 x 8 cm., immersed in a glass of water, so that its 3 x 5 cm. face is parallel to the surface of the water, and 6 cm. below it (Fig. 39). The downward push on the top of the block will be equal to the weight of a column of water 3 x 5 x 6 cm., that is, 90 g. The upward push on the bottom of the block will be equal to the weight of a column of water 3 x 5 x 14 cm., for the bottom of the block will be 14 cm. below the surface of the water. This upward push will therefore be equal to the weight of 210 c.c. of water, or, 210 g. The pushes on the two vertical 3 x 8 cm. sides will just balance, as will the pushes on the two vertical 5 x 8 cm. sides. This is shown by the fact that the block does not tend to move sideways.

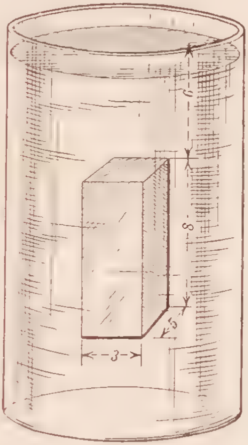

Fig. 39. Proof of Archimedes' Principle

If the upward push is 210 g., and the downward push is 90 g., the difference, or 120 g., must be the net upward force, or, the apparent loss of weight of the block. Since the block has a volume of 3 × 5 × 8 cm. = 120 c.c., and since 120 c.c. of water weighs 120 g., it follows that the block is buoyed up by a force equal to the weight of the displaced water.

State Archimedes' principle. Who was Archimedes? How would you prove mathematically that Archimedes' principle holds true?

52. Floating Bodies.—Sometimes the upward push of the water is more than the downward pull of the weight of the body. In such cases the body floats. Imagine a cork below the surface of water. The upward push of the water is more than the downward pull due to the weight of the cork. The cork will therefore start to rise. As soon as it begins to rise above the surface of the water, the part of the cork that is out of the water is no longer buoyed up by the water, because it no longer displaces any water. This diminishes the upward push, and the effect increases as more of the cork leaves the water. Finally, the upward push of the water and the downward pull of the weight of the cork just balance each other, and the cork then floats in equilibrium. This will occur when the floating body displaces its own weight of water. Icebergs float, because a cubic foot of ice weighs less than a cubic foot of water.

Archimedes' principle is true no matter what liquid is used. In the case of floating bodies, the heavier (denser) the liquid used, the higher the body will float; for, the heavier the liquid, the less volume of it is required to weigh the same as the floating body. For this reason iron will sink in water but float on mercury. Since salt water is heavier, volume for volume, than fresh water, our bodies are buoyed up more by salt water than by fresh water, and it is therefore easier to swim in smooth salt water than in a fresh water lake. In Great Salt Lake, which is an almost saturated solution of salt and therefore very dense, it is possible to stand upright in the water and float with the shoulders out of the water. Do you think, then, that it would be possible to swim in mercury?

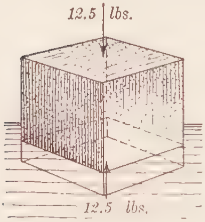

FIG. 40. Buoyancy of Cork

Assume that a cubic foot of cork weighs ⅕ as much as a cubic foot of water. If such a cube be placed on water, it will sink, until the water displaced weighs as much as the cork. It will therefore displace ⅕ of a cubic foot of water, and it will float $\frac{4}{5}$ out and $\frac{1}{5}$ in the water. This buoyancy of cork is taken advantage of in life preservers. (Fig. 40.)

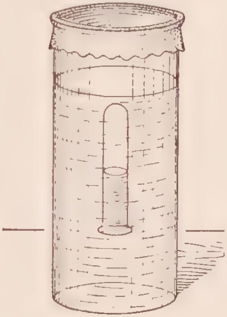

FIG. 41. Cartesian Diver

A "Cartesian diver" is a light, hollow glass figure, having a small hole in the bottom. Enough water is introduced into the figure, through this hole, to make it just float in water. The diver is then placed in a jar of water that is covered with a rubber top. When this rubber top is pressed down, the air in the diver is compressed, and more water passes into the diver. The figure then sinks. Releasing the air pressure causes the figure to rise. You can easily make such a Cartesian diver, using an inverted test-tube, instead of the glass figure (Fig. 41).

Under what condition does a body float? Why is the buoyant force less while the body is floating than while it is immersed? What determines how much of a floating body will remain under water? Will a ship sink lower in fresh water or in salt water? Why? Why is cork often used in life preservers?

What is a Cartesian diver? What makes him sink? What makes him float?

53. Applications of Archimedes' Principle.—An iron ship floats because it is hollow, and acts like a body that, if submerged, would displace more than its own weight of water. In building ships, the naval architect knows in advance the weight of the materials to be used and the volume of the hull, and he can calculate just where the water line will come, and how far the cargo will sink the ship.

A *submarine* (Fig. 42) is built of such a weight and volume that it will displace just enough water to float. When tanks, contained in the hull, are filled with water, thus increasing

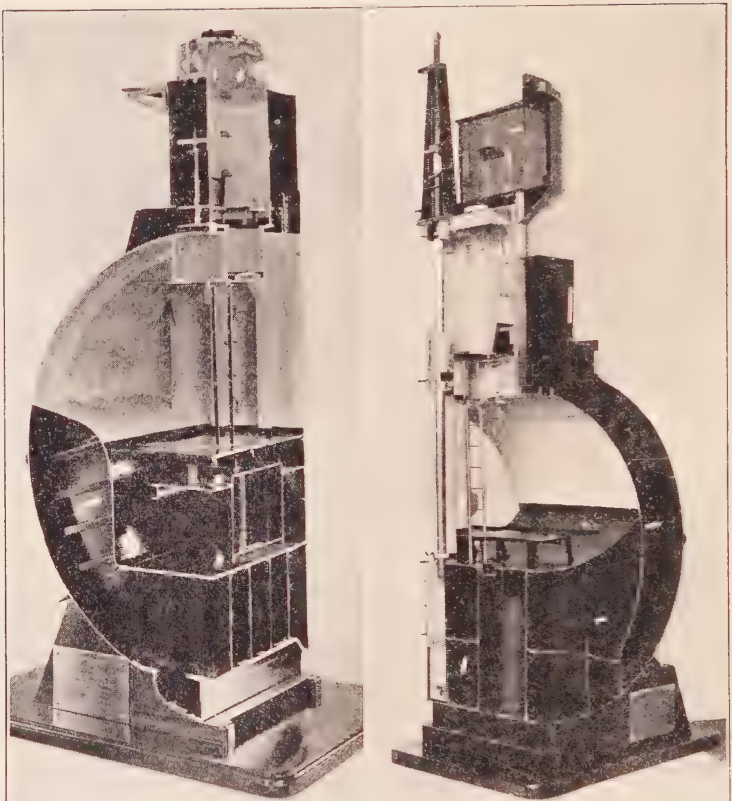

FIG. 42. Cross Section of a Submarine Model

Single Hull Type Double Hull Type

the weight, the submarine will sink. Emptying the tanks, by using powerful pumps, reduces the weight, and the submarine rises. Notice how similar, in these respects, the submarine and the Cartesian diver are.

Sunken vessels are frequently raised by lowering large iron tanks (caissons) on each side of the wrecked vessel, passing chains under the hull, and connecting them to the tanks (Fig. 43). When the water is pumped out of the caissons, the buoyant force becomes great enough to raise the vessel.

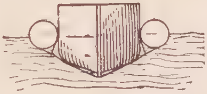

FIG. 43. Floating a Wreck by Means of Caissons

54. Diving Suits.—A diver wears a water-tight suit and a copper helmet, with a glass front through which he can see. His helmet has two openings, one fitted to an air pipe and the other to a check valve. Air is forced down to the diver through his air pipe by a pump at the surface, while the air he breathes out escapes through the check valve. As the diver descends, the pressure of the water becomes greater, and soon a point is reached where it is impossible to endure it. It is an interesting problem to compute the pressure on a diver at a depth of a hundred feet. If you will do this you will see why the common notion that divers might be used to recover the treasure lost in deep sea wrecks is wrong. Jointed metal suits are now sometimes used for greater depths (Fig. 44).

Why does a ship float even though made of iron? How can the ship designer tell where the water line will be? What makes a submarine float? How may it be made to sink? How is it brought to the surface? Explain how caissons containing air can be used to float a vessel resting on the bottom of the sea. How is a diver's suit made? What limits the depth to which the diver can go?

55. Specific Gravity and Density.—By *specific gravity* we mean the weight of a body compared to the weight of an equal volume of water. The specific gravity of cast zinc is 7, that is, a cubic foot of zinc will weigh 7 times 62.5 pounds = 437.5 pounds.

$$\textbf{Specific gravity} = \frac{\textbf{Weight of body}}{\textbf{Weight of an equal volume of water}}$$

Density is the number of units of mass of a substance con-

FIG. 44. Metal Diving Suit

tained in a unit volume. The units used must always be stated.

$$\textbf{Density} = \frac{\textbf{Mass}}{\textbf{Volume}}$$

Specific gravity is a ratio and is the same no matter what system of units is used. *Density* varies with the units used.

The specific gravity of mercury is 13.6. The density of mercury is 13.6 grams per c.c., or, 850 lb. per cu. ft. In the metric system 1 c.c. of water weighs 1 g., and the density of water is therefore 1 g. per c.c. In the metric system then, the density of any substance expressed in grams per cubic centimeter has the same numerical value as the specific gravity, but this is not true in English units. We must therefore take care not to confuse specific gravity and density.

Define specific gravity. Define density. Distinguish between specific gravity and density. Why is it necessary to use units in expressing density while it is not necessary in expressing specific gravity? If the specific gravity of glass is 2.5, what is its density in English units? In metric units?

56. To Determine the Specific Gravity of a Solid.—Weigh the object in air. Find the weight of an equal volume of water. Divide the weight of the object by the weight of the equal volume of water. The result is the sp. gr. The best method of finding these weights will depend on the specimen to be tested.

The simplest case is where the object is a regular geometrical solid, such as a cube. In this case we can weigh the body and find its volume by measurement. We then calculate the weight of an equal volume of water. The sp. gr. is found by dividing the first weight by the second.

In the case of a powder that is insoluble in water, we can first weigh it, and then pour it into a graduated cylinder that is partly filled with water. By reading the initial volume of water in the cylinder, and the volume after the powder has been poured in, we can obtain the volume of the powder. Knowing this we can calculate the weight of an equal volume of water. Division then gives the sp. gr. This method can, of course, be used in the case of a body of irregular shape. The method is simple but has the disadvantage that it is hard to read the graduate accurately enough to get the volume exactly, and air, mixed with the powder, adds to its apparent volume.

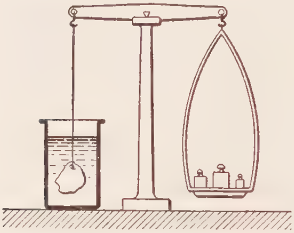

FIG. 45. Determining Specific Gravity

A better method in the case of an irregular solid is first to weigh the body in air, and then suspend it from the beam of a balance, in such a way that it hangs immersed in a glass of water (Fig. 45). Weighing it again gives a smaller weight than before, because the body is buoyed up by the water. The difference between these two weights is the buoyant effect of the water. This is equal to the weight of the volume of water displaced by the body (Archimedes' principle), that is, the weight of an equal bulk of water. For example: if a piece of zinc weighs 140 g. in the air, and 120 g. when immersed in water, the apparent loss of weight, 20 g., is the weight of an equal volume of water. The sp. gr. is then: $140 \div 20 = 7$.

Outline the procedure for finding the specific gravity of a solid. How can you find the volume of an irregular body? How can you find the volume of a powder? How can you find the weight of water equal in volume to the volume of the solid? Why is the buoyant force the same as the weight of an equal volume of water? What does it mean to say that "the specific gravity of mercury is 13.6"?

57. To Determine the Specific Gravity of Solids Lighter Than Water.—When a body is lighter than water, a different method must be used. Since the body would float if placed in water, it is necessary to use a sinker to immerse it. Weigh the body in air. Weigh the sinker in air and in water, and take the difference; this is the displacement of the sinker. Tie the body to the sinker and weigh both immersed in water. From the combined weight of the two in air, subtract the combined weight of the two in water. This gives us the apparent loss of weight of the two in water. If we subtract from this the apparent loss of weight of the sinker alone, which we have already found, the difference will be the loss of weight of the body. Then, the weight of the body in air, divided by its apparent loss of weight when immersed in water, equals the sp. gr. The problem below illustrates the method.

Weight of body in air = 8 grams
Weight of sinker in air = 21 ”
Weight of sinker in water = 11 ”
Weight of both in water = 7 ”
Loss of weight of sinker in water = 21 — 11 = 10 ”
Weight of both in air = 21 + 8 = 29 ”
Loss of weight of both in water = 29 — 7 = 22 ”
Loss of weight of body in water = 22 — 10 = 12 ”
Specific gravity = sp. gr. = 8 ÷ 12 = 0.66

If we have to determine the sp. gr. of rock candy, these methods will fail, because the rock candy (sugar) will dissolve in water. In this and similar cases we may use kerosene or some other liquid in which the body is not soluble. Knowing the sp. gr. of kerosene, we can determine the ratio of the sp. gr. of the body to that of kerosene, and then find the sp. gr. of the body itself. The sp. gr. of kerosene is 0.79. If a body is four times as heavy as an equal volume of kerosene, it will be 4 × 0.79 times as heavy as an equal volume of water, that is, its sp. gr. will be 3.16.

If a solid is lighter than water, how can you find the weight of an equal volume of water? What is the purpose of the sinker? How do you find the displacement of sinker and body? Of the sinker? Of the body alone? If the body whose specific gravity is desired is soluble in water, what means will you employ?

58. Specific Gravity of Liquids.—A simple method for determining the specific gravity of liquids is to weigh a clean, dry, glass-stoppered bottle. Fill the bottle with water and weigh again. The difference in these weights is the weight of water required to fill the bottle. Empty and dry the bottle, and fill it with the liquid, the specific gravity of which we wish to determine. Weigh it. The difference between this weight and the weight of the empty bottle is the weight of the liquid. We now have the weight of equal volumes of water and the liquid, and by dividing we can obtain the specific gravity.

Weight of bottle dry and empty =	37	grams
Weight of bottle full of water =	87	”
Difference = weight of water =	50	”
Weight of bottle dry and empty =	37	”
Weight of bottle full of copper sulphate solution =	91	”
Difference = weight of copper sulphate solution =	54	”

Sp. gr. of copper sulphate solution = 54 ÷ 50 = 1.08

It is difficult to fill ordinary bottles and put in the stopper without leaving an air bubble in the bottle. To avoid this, special bottles, called *specific gravity bottles* (*pycnometers*) are used (Fig. 46). These usually have the volume and weight marked on the bottles, so that it is unnecessary to weigh the bottle full of water. The glass stopper has a very small hole pierced through it, so that, when the bottle is filled with the liquid to be studied and the stopper is inserted, any excess liquid can pass out through the hole.

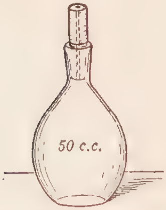

Fig. 46. Specific Gravity Bottle

Another method is to weigh a piece of glass in air, and then weigh it again, suspended first in water, and then in the liquid to be studied. Find the loss of weight of the glass in water and the loss of weight of the glass in the liquid. The loss of weight in the water is the weight of a volume of water equal to that of the solid, and the loss of weight in the liquid is the weight of an equal volume of the liquid. The specific gravity is then the loss of weight in the liquid divided by the loss of weight in water. In practice the glass pieces used are marked with their weight and volume, so that it is only necessary to weigh them in the liquid.

a = Weight of glass in air = 20 grams
b = Weight of glass in water = 15 ”
c = Weight of glass in copper sulphate solution = 14.6 ”
$d = (a—b)$ = Weight of displaced water =
(20—15) = 5 ”
$e = (a—c)$ = Weight of displaced copper sulphate
solution = (20—14.6) = 5.4 ”

Since d and e are the weights of equal volumes of water and copper sulphate solution, the specific gravity = 5.4 ÷ 5 = 1.08 = sp. gr. of copper sulphate solution.

What is a specific gravity bottle? How is it used? Why is there a small hole through the stopper? Given a marble, a balance, and a liquid whose specific gravity is desired, how would you proceed? Why is the loss of weight of the marble different in water and in the other liquid? A marble loses in weight 5 grams in water and 4 grams in alcohol. What is the specific gravity of the alcohol?

59. **Hydrometers.**—The simplest method of determining the specific gravity of a liquid is by the use of a hydrometer. It is usually made of glass and consists of a cylinder that is closed at the bottom and weighted to make it float upright. The upper part is a narrow glass tube with an inclosed scale. The hydrometer is first floated in water, and the point to which it sinks is marked on the scale. It is then floated in some liquid of known specific gravity, and the point to which it sinks is marked on the scale. These two points being known, the scale can be divided and the other points marked on it. (Fig. 47.) The liquid to be tested by the hydrometer

is placed in a hydrometer jar (a glass cylinder), and the hydrometer is inserted. The point to which it sinks is noted on the scale, and this gives the specific gravity of the liquid.

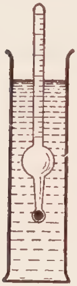

FIG. 47. Hydrometer

By making the bulb of the hydrometer large and the tube containing the scale small, hydrometers can be made so as to give results correct to the third decimal place. They are used commercially in many industries, as in the making of acids, and for testing the liquid of storage batteries.

What is a hydrometer? Describe a hydrometer. How are the positions of the numbers on the scale determined? Is the largest number always at the top of the scale or always at the bottom? Why is the bottom of the hydrometer weighted? Mention some uses of a hydrometer.

60. Lactometers.—Milk is a very valuable food. Its specific gravity may vary from 1.026 to 1.036, depending on the breed of the cow and its food. An unscrupulous milkman might easily add to ten gallons of rich milk one half a gallon of water, without materially changing the appearance or taste of the milk. To prevent this, a special hydrometer, called a *lactometer,* with a scale reading from 1.020 to 1.040 is used. By the use of the lactometer the watered milk can be detected, because its specific gravity will be too low. This is not, however, an absolute test, for if the dealer should first skim the milk, the specific gravity would be increased. Watering this would then lower the specific gravity, leaving it finally within the legal limits. This fraud can be detected by other tests.

What is a lactometer? Why is it desirable to test the specific gravity of milk? Is the specific gravity of the milk a sufficient proof of its food value? Explain.

Densities and Specific Gravities

	DENSITY in g. per c.c. = SP. GR.	DENSITY in lb. per cu. ft.		DENSITY in g. per c.c. = SP. GR.	DENSITY in lb. per cu. ft.
Aluminum	2.57	160.5	Marble	2.65	165
Brass (yellow)	8.44	527	Mercury	13.596	848
Charcoal (oak)	0.58	35	Paraffin	0.89	55.5
Copper (cast)	8.88	553	Platinum	21.45	1338
Glass (common)	2.61	163	Quartz	2.65	165
Granite	2.75	171	Silver (cast)	10.45	652
Ice	0.917	57.3	Tin (cast)	7.29	455
Iron (gray-cast)	7.08	442	Zinc (cast)	7.10	443
Iron (wrought)	7.85	489			

EXERCISES

1. What is the reason for the buoyant effect of liquids?

2. Why does an iron ball sink and an iron ship float?

3. Does a ship float deeper in fresh or in salt water?

4. Upon what factors does buoyancy depend?

5. Why does a balloon finally stop rising while a body that goes below the surface of a fluid always goes to the bottom?

6. If you had Archimedes' problem of the crown to solve, just what would you do, and what facts would you have to know before you could answer the question?

7. People can float in water without moving. How does it happen then that people sometimes drown?

8. Why do stout people usually float better than thin people?

9. What is the difference between density and specific gravity?

10. How could you determine the specific gravity of sugar?

11. How could you determine the specific gravity of vinegar?

12. How could you determine the specific gravity of cork?

13. How is a hydrometer constructed and used?

14. What is the purpose of the bulb in the middle of a hydrometer? Might the weight be above the bulb?

15. How would the Cartesian diver behave if the jar were a very deep one?

16. Some men cannot float with their feet near the surface. Explain.

17. What substances in the table of densities will float in water, and what in mercury?

18. What happens when oil is poured into water and why?

19. Why will a bad egg often float in water, while a fresh egg will sink?

PROBLEMS

1. A body weighs 8 lb. in air. When suspended 1 ft. below the surface of water its apparent weight is 7 lb. What will its apparent weight be when suspended 3 ft. below the surface?

2. Assume that in the ocean you float 19/20 immersed. Knowing your weight, can you find the volume of your body?

3. What must be the volume of a body weighing 50 grams, if it is to float half immersed in water?

4. A body weighs 18 g. in air and 16 g. immersed in water. What is its sp. gr.? What is its volume in c.c.?

5. The sp. gr. of platinum is 21.6. If you can lift 100 lb., how many c.c. of platinum can you lift?

6. A glass bulb loses 2.4 g. when immersed in water, and 2.2 when immersed in oil. Find the sp. gr. of the oil. If the sp. gr. of turpentine is 0.87, what will the bulb lose when immersed in turpentine?

7. A cu. ft. of hard coal weighed 90 lb. Will it float on water? What is its sp. gr.?

8. A cut gem weighed 60 mg. in air and 50 mg. in water. The sp. gr. of the diamond is 3.5. Was the stone a diamond?

9. A rectangular floating dock is 15 x 30 ft. If 40 people, of an average weight of 150 lb. stand on it, how far will it sink?

10. The sp. gr. of ice is 0.92. If an iceberg has a volume of 500 cu. ft. out of the water, what is its volume under water?

11. A graduate is filled with water to the 100 c.c. mark. A lump of brass weighing 93.5 g. was dropped in, raising the water to the 111 c.c. mark. What is the sp. gr. of brass?

12. A sp. gr. bottle holding 50 c.c. will contain 91.5 g. of sulphuric acid. What is the sp. gr. of the acid?

13. Assume that Hiero's crown weighed 965 g. in air, and 905 g. in water. The sp. gr. of gold is 19.3 and of silver 10.5. Did the crown contain silver?

14. A cu. dm. of brass is immersed in water. (a) What volume of water does it displace? (b) What weight of water does it displace? (c) What is the buoyant force exerted on the brass? (b) What buoyant force would be exerted on a cu. dm. of gold?

15. A cu. ft. of stone weighing 156 lb. is thrown into water. If you can lift 100 lb., can you lift the stone while it is under the water?

16. A body weighing 40 g. in air, weighs 30 g. in water. (a) What is its volume? (b) What is its sp. gr.? (c) What is its density in g. per c.c.? (d) What is its density in lb. per cu. ft.?

17. An aluminium bar weighs 26 g. in air, and 16 g. in water. Find its volume and sp. gr.

18. A stone weighs 12.5 grams in air, 7.5 g. in water, and 8.5 g. in alcohol. (a) What is the volume of the stone? (b) What is the sp. gr. of the stone? (c) What is the sp. gr. of the alcohol?

19. A block of wood weighs 1 lb. in air. It is attached to a sinker that weighs 4 lb. in water. Both together weigh 3.2 lb. in water. Find the sp. gr. of the wood.

20. A diver in his diving suit weighs 250 lb. If his volume is 5 cu. ft., how far will he sink? What weight of lead would be required to sink him?

CHAPTER VII

LIQUIDS IN MOTION

61. Water Wheels.—When we open a stopcock in a pipe connected to the bottom of a reservoir, pressure causes the water to flow through the pipe. If the height of water in the reservoir is considerable, the water will flow so swiftly that it will possess great energy, and this energy may be used to turn a water wheel. The overshot and the undershot wheels are two simple forms of water wheels. The *overshot wheel* is a large wheel having buckets on the rim (Fig. 48). The wheel is so placed that water flows into these buckets and causes the wheel to rotate. It is used where the supply of water is small, but its head considerable. The *undershot wheel* (Fig. 49) has a series of paddles on the rim. It is so placed that the flowing water strikes against these paddles and causes the wheel to rotate. It is used where the supply of water is large, but the head small. An improved form of the undershot wheel is the *Pelton wheel,* in which water from a nozzle acts on cup-shaped buckets, mounted on the edge of the wheel (Fig. 50). This form is often used for small power installations.

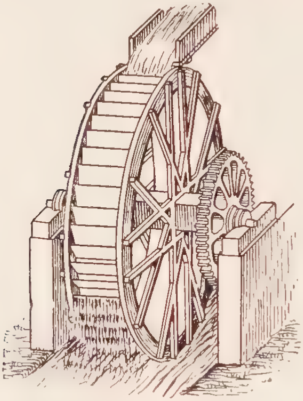

Fig. 48. Overshot Water Wheel

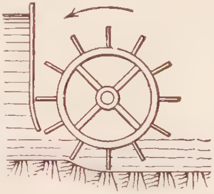

Fig. 49. Undershot Water Wheel

What use can be made of the energy of running water? What is an overshot wheel? An undershot wheel? Describe each. What is a Pelton wheel? What purpose do all these wheels serve?

62. Turbine Water Wheels.—This is the form most used today. It has a stationary outer case, with blades so placed as to direct the water against the blades of the rotating inner case (Fig. 51): The turbine is placed at the bottom of a shaft and stands completely under water in a casing. It rotates in a horizontal plane.

At Niagara vertical holes have been dug in the bed of the stream above the Falls. At the bottom of these holes (pits), large turbine water-wheels are placed (Fig. 52). As the water rushes down through the pit it passes through openings in the turbine case, which direct it so that it strikes against the inner blades at the most effective angle, forcing them to rotate. The water then passes from the bottom of the pit, through a tunnel (tailrace), back to the river below the Falls. The rotating part (rotor) is connected by a steel shaft to an electric generator at the surface of the ground, and this produces an electric current, which is used to light Buffalo and to furnish power to factories. In many parts of the country where waterfalls exist similar plants, called hydro-electric plants, are in operation. They furnish a cheap source of energy.

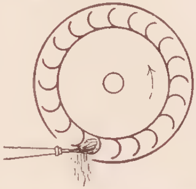

FIG. 50. Pelton Water Wheel

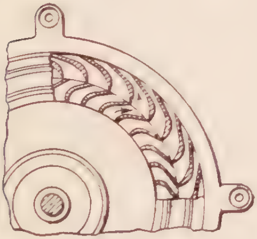

FIG. 51. Turbine Water Wheel

Describe the turbine water wheel. Where is the turbine wheel placed? Describe the installation of turbines at Niagara Falls. What use is made of the energy developed by the falling water? In what

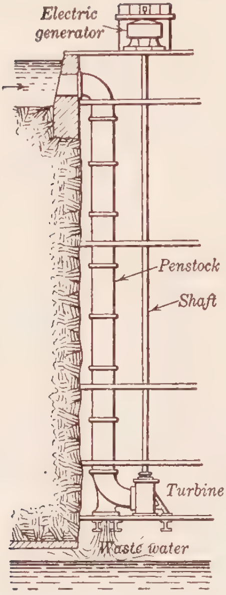

FIG. 52. Power Plant at Niagara Falls

form is the energy used? Why is water power preferred to power obtained by burning coal?

63. House Water Motors.—When the water pressure at a faucet is reasonably high, a small Pelton water wheel may be attached directly to the faucet and used to run small polishing wheels, grinding wheels, etc. In principle these are like the large Pelton wheels (Fig. 53).

How is it possible to use water power directly in the home? What style of water wheel is used in house motors?

64. The Hydraulic Ram.—This is a device for utilizing the energy of a large quantity of water, falling a short distance, to raise a small quantity of water a considerable distance. It makes use of the principle of inertia. A pipe A (Fig. 54), through which a stream of water flows, contains at V a valve that is normally open, but is closed by the flowing water, when the latter has gained a certain velocity. When this valve closes, the sudden stoppage of this outlet causes the water, by its inertia, to force open the second valve Q, driving the water into the air chamber C. This increases the air pressure in C. The increased air pressure soon stops the flow of water into C and momentarily forces some of the water back through the pipe A, at the same time closing the valve Q. The water in the pipe having now come to rest, the valve V opens, and the ram is in its original condition, except that a small amount of water has been forced into C. The whole operation is repeated 30 or more times a

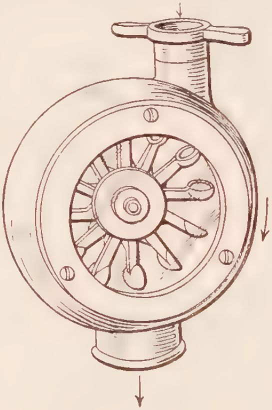

FIG. 53. House Water Motor

minute. Soon the air pressure in C increases to such an amount that water is forced from C out through the pipe E to an elevated tank.

The ram is very inefficient, but, where a brook or any flowing water is available, it is a cheap method of pumping water to a height. In such cases its inefficiency is of no consequence, as the energy of the brook would otherwise be wasted. The ram has the great advantage of requiring little attention.

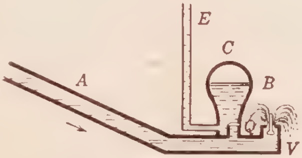

FIG. 54. Hydraulic Ram

What is the purpose of a hydraulic ram? What causes valve V (Fig. 54) to close? Valve Q to open? Where does the water go when valve Q opens? What effect is produced in C? What is the result of this? What closes the valve Q? Why does the valve V open? What has been accomplished by all these changes? Is the hydraulic ram an efficient form of pump? Why then is it used?

EXERCISES

1. Under what conditions would an undershot water wheel be used? An overshot wheel? Why have these two forms almost passed out of use?

2. Explain the principle of the turbine water wheel. How is its energy utilized at Niagara?

3. Explain the principle of the hydraulic ram. Why does the valve into the air chamber open?

4. What great advantage has Norway for developing water power?

5. Sketch, describe, and explain the Pelton wheel. How does it differ from the turbine wheel?

6. Describe and explain the principle of the house water-motor. Why does it require high water-pressure?

CHAPTER VIII

GASES. THE ATMOSPHERE.

65. The Air.—We live at the bottom of an ocean of an invisible, odorless gas, that we call air. Air is the gas with which we are most familiar, and, in discussing the properties of gases, we shall use it as the example. You must remember, however, that the laws that apply to air apply to all other gases as well.

That air has weight is easily shown by weighing a burnt-out incandescent lamp (not a gas filled lamp). Heat a spot on the lamp red hot, using a mouth blowpipe. The air pressure on the outside will force a hole through the softened glass, and the lamp will fill with air. Weigh again and you will find the weight increased, owing to the air taken in. If you determine the volume of the lamp by filling it with water, you have all the figures necessary to determine roughly the weight of one cubic foot of air. The weight of a cubic foot of air at 0° C. and 76 cm. pressure has been found to be .081 pound, or, roughly, 12 cubic feet of air weigh a pound. The inertia of air, combined with a high velocity, makes violent winds very destructive, and because of its inertia it offers great resistance to rapidly moving objects.

How can you prove that air has weight? How much does a cubic foot of air weigh? How many cubic feet of air weigh a pound? Why are winds destructive? Is air a typical gas? Could what we learn about air be applied to other gases?

66. Pressure of the Atmosphere.—Since air is a fluid and has weight, it must press down on the surface of the earth.

Fill with mercury a long glass tube that is closed at one end. Cover the open end, and, after inverting the tube, stand it in a dish of mercury, with the open end beneath the surface of the mercury (Fig. 55). Since the end that is in the mercury is open, you would naturally expect all of the mercury to run out. Some does run out, but a column about 30 inches high remains in the tube. The only thing that can keep the mercury in the tube is the pressure of the air on the mercury in the dish. By measuring the cross-sectional area of the tube and weighing the mercury it contains, we find that if the tube had had a cross section of one square inch, the mercury would have weighed about 15 pounds. Hence the air exerts on the surface of the earth at sea level a pressure of about 15 pounds (more accurately 14.7 pounds) per square inch. This, then, must be the weight of a column of air, reaching from the ground to the top of the atmosphere and one square inch in cross section.

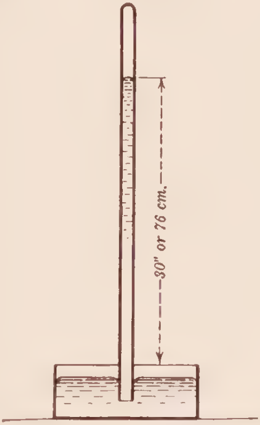

Fig. 55. Simple Barometer

This pressure of 15 lb. per sq. in. is often spoken of as a pressure of *one atmosphere,* but the figure 15 is only approximate, for the pressure varies with the altitude of the place where the measurement is made and the height of the barometer at the time.

Since we filled the tube with mercury before inverting it in the dish of mercury, and since nothing else could get into the tube, the space above the mercury must be empty, except for a small amount of mercury vapor. We call such an empty space a *vacuum.* This experiment with mercury in a tube was first tried by an Italian named Torricelli, and the vacuum above the mercury is therefore called a *Torricellian vacuum.* Such a tube, containing mercury that is held up by the pressure of the air, is called a *barometer* (Fig. 56). At sea level and under ordinary conditions of the air, the barometer reads about 30 inches, or about 76 cm.

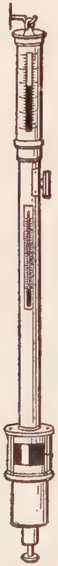

FIG. 56. Weather Bureau Barometer

How can you show by an experiment that air exerts a pressure upon surfaces immersed in it? How high will the pressure of the air hold a column of mercury? What is meant by the pressure of one atmosphere? What is a vacuum? A Torricellian vacuum? What is a barometer? How high does the barometer usually stand at sea level?

67. Use of Barometer in Foretelling Weather Conditions.—It has been found that a falling barometer generally indicates an approaching storm, while a rising barometer predicts clearing weather. Storms are usually due to great whirlwinds of air covering hundreds of square miles, the pressure decreasing toward the center of the whirl. The U. S. Weather Bureau issues daily a map showing the barometric readings, wind directions, etc., throughout the country. From these maps and our knowledge of the general behavior of storms, the probable path of a storm can be predicted. Figure 57 shows such a weather map.

What is the usual cause of rainstorms in the United States? Does the barometer rise or fall before a storm? How then can the barometer be used to predict the weather? What is a weather map? What purpose do weather maps serve?

68. Aneroid Barometers.—The mercury barometer is very accurate, but it is large and fragile. When we wish to carry

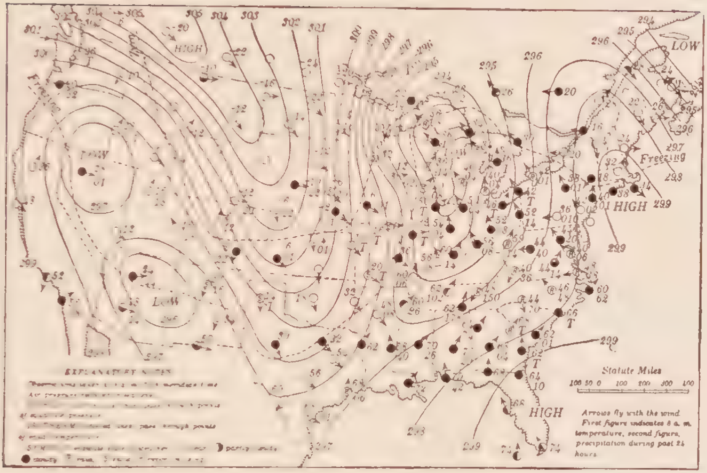
HIGH
LOW
Low
HIGH
HIGH
Freezing
Freezing
Statute Miles
100 50 0 100 200 300 400
Arrows fly with the wind.
First figure indicates 8 a.m. temperature, second figure, precipitation during past 24 hours.

Fig. 57. Weather Map

a barometer about, we use another form called an *aneroid barometer* (Fig. 58). This is a sealed metal box, the top of which is made of thin corrugated metal. The air is partly exhausted from the box. As the atmospheric pressure varies, the top of the box moves in or out. This change in shape is too small to be seen, but the motion is magnified by connecting a series of levers to the center of the top of the box. The last lever has a pointer that moves over a graduated scale, the graduations of which correspond to inches on the mercury barometer, so that the pressure can easily be read. Usually, a second movable pointer, not connected with the mechanism, is mounted over the barometer pointer. This second pointer can be moved from the outside

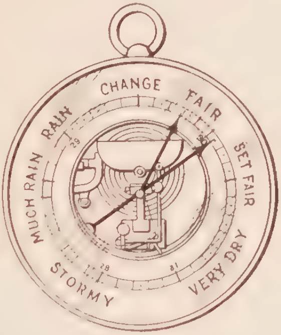

Fig. 58. Aneroid Barometer

of the barometer case. By placing it exactly over the real barometer pointer and looking at their relative positions a few hours later, we can tell whether the barometer is going up or down. It is not the height of the barometer, but the direction in which the pressure is changing, that enables us to predict changes in the weather.

Aneroid barometers are made so sensitive that, by reading the air pressure at the bottom of a tall building, and then carrying the aneroid to the roof, the change in air pressure due to the height of the building can be measured. An elevation of 90 feet will change the barometer about 0.1 inch. The aneroid barometer, fitted with a special scale, is used by aviators in determining their altitude. Such a special form of barometer is called an *altimeter.*

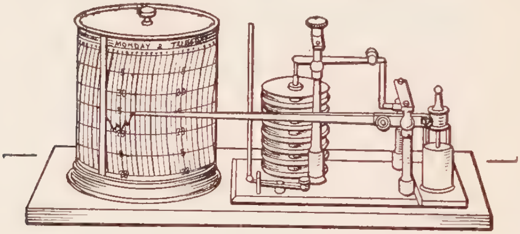

Fig. 59*a*. Barograph

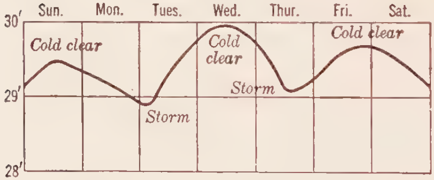

Fig. 59*b*. Barograph Record

Sometimes a registering barometer, called a *barograph,* is used. The end of the barometer pointer carries a pen that rests on a chart, which is moved by clockwork. (Fig. 59*a*.) The pen traces on the chart the position of the pointer from day to day, and, by examining the chart at the end of the week, the changes in the air pressure during the week can be read. It also shows us whether the air pressure is rising or falling, and this helps us to foretell changes in the weather, as is shown by the record in figure 59b.

What disadvantage does a mercury barometer have? What is an aneroid barometer? Describe its construction. Why is some of the air removed from the box? What is the purpose of the second pointer sometimes placed on the aneroid barometer? What other use has a barometer besides predicting the weather? What is a barograph? What advantage has it over a barometer?

69. Crushing Force of Air.—A simple experiment that will make atmospheric pressure real to you, and that you should try at home, is to fill a tumbler with water, cover it with a piece of paper, and then quickly invert it. The downward pressure, due to the weight of water, is more than counterbalanced by the upward pressure due to the air, and the water is therefore held in the tumbler. This is because, by Pascal's law, which is true of all fluids, the air pressure will act upward with a pressure of 15 lb. per sq. in. (Fig. 60), while the downward pressure of the water is much less.

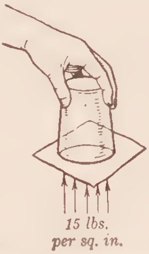

Fig. 60. Air Pressure Acts in All Directions (Pascal's Principle)

To illustrate what would happen to our bodies if the air pressure inside and outside were not the same, pour water into a tin can to a depth of half an inch, and boil the water vigorously for a few minutes. The steam formed will drive out the air. When all the air has been expelled, remove the flame and quickly cork the can. Cool it under a stream of water, thus condensing the steam and creating a partial vacuum in the can. The can will be crushed by the pressure of the outside air (Fig. 61).

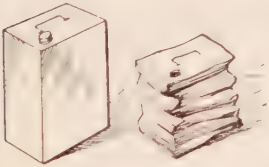

Fig. 61. Crushing Force of Air

In figure 60 what holds the card on the bottom of the tumbler? Why does not the pressure of the air crush in our bodies as it did the can in figure 61? Why was it necessary to condense the steam in the can before the air would crush it?

70. Boyle's Law.—Gases are highly compressible. If a graduated U-shaped tube, open at one end, and having a stopcock at the other (Fig. 62), is partly filled with mercury while the stopcock is open, and the stopcock is then closed, the air in the tube must be under atmospheric pressure. By pouring additional mercury into the open end, the pressure on the air can be increased, and, by measuring the height of mercury in the two arms, the increased pressure can be found. By measuring at the same time the new volume of the confined air, the change in volume due to a change in pressure can be found. When the volume of the air is measured under different known pressures, it is found that: **The volume of a gas varies inversely as the pressure, if the temperature is kept constant.** This is known as Boyle's law, because it was discovered by Robert Boyle at Oxford in 1662.

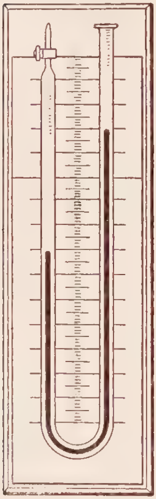

FIG. 62. Boyle's Law Apparatus

Let the original volume of the gas be V, and the original pressure P. When the pressure changes to P', the volume changes to V'. Then by Boyle's law:

$$\frac{\mathbf{V}}{\mathbf{V'}} = \frac{\mathbf{P'}}{\mathbf{P}}, \text{ or } \mathbf{PV} = \mathbf{P'V'}$$

Putting this into words: **The product of pressure and volume of a given mass of gas is a constant, if the temperature re-**

mains the same. The necessity for mentioning temperature will be seen when you study Heat.

Boyle's law is only approximately true, especially at high pressures, but it is sufficiently accurate to be of great help in computing gas volumes.

How can you prove that gases are compressible? If the pressure on a gas is doubled, what will happen to its volume? If the pressure is reduced to one-third? State Boyle's law. Is Boyle's law a newly discovered law? Is Boyle's law strictly true at all pressures and with all gases? What use is made of Boyle's law?

Pumps and Their Uses

71. Check Valves.—In the next few pages we are to study pumps. It will help us to understand their action if we first learn what a check valve is and how it works. A check valve is a device for allowing a fluid (liquid or gas) to flow through a tube in one direction, but not in the other. The simplest form is shown in figure 63. Across the tube is placed a diaphragm with a hole in the center. Over this hole is placed a flap, hinged at one side. A fluid can easily pass in the direction that will lift the flap. As soon, however, as it tries to pass in the opposite direction, the flap is pressed tightly against the diaphragm, and the pipe is closed. Such valves are often used in industrial plants.

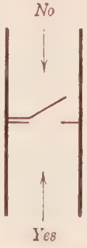

Fig. 63. Check Valve

What is a check valve? What is the purpose of a check valve? Describe a simple check valve.

72. Air Pumps.—Air pumps are of two kinds,—those that compress air into a vessel, and those that exhaust air from a vessel.

A simple air compressor, used to pump up bicycle and automobile tires, is a brass cylinder with a check valve in the base, so placed that air can pass down but not up (Fig. 64). In the cylinder there is a piston that ends in a leather cup. The cup acts as a check valve that works in the same direction as the valve in the base. A strong hose leads from the base of the pump to the tire that we wish to inflate. When we push the piston down, the leather cup is then pressed so tightly against the cylinder that no air can leak by it. The air is therefore compressed in the cylinder, until the valve in the base opens and air is forced through the hose into the tire. As we raise the piston, the check valve in the base closes, preventing the escape of air from the tire, while the leather cup falls away from the sides of the cylinder and allows air to enter. When the piston has reached the top of its stroke, the pump is again full of air, and the operation is repeated.

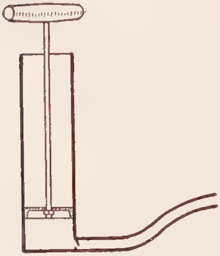
Fig. 64. Automobile Hand Pump

Air pumps used for exhausting air are just like air compressors, except that the check valves work in the opposite directions, thus enabling us to pump the air out of a vessel. Their action depends on the expansive force of the air. The first was invented by Otto von Guericke of Magdeburg, in 1650.

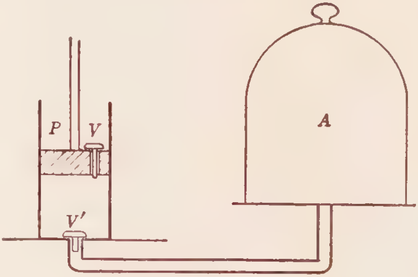

Fig. 65. Air Pump

An air pump used to produce a vacuum is shown in figure 65. As the piston *P* is raised, the air above it in the cylinder is pushed out, and the air in the vessel *A* expands to take its place, the check valve V' opening to allow this. On pushing the piston down, the valve V opens, allowing the air below the piston to escape, while the valve V' closes and prevents air from passing back into A. If the vessel and cylinder had the same volume and the operation were perfect, one stroke of the piston would remove one half of the air from the vessel. A second stroke would remove one half of the remaining air. In this way, a good, but never a perfect, vacuum could be obtained. Even though the check valves are made of thin oiled silk, the exhaustion soon reaches a point where the expansive force of the air will not lift them. In the best pumps these valves are therefore worked mechanically.

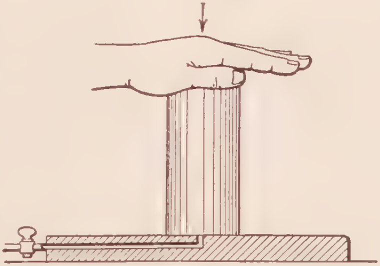

FIG. 66.

Such a simple air pump allows us to show many interesting experiments. If a cylinder open at both ends is placed over the air pump plate (Fig. 66), the hand placed over the open end, and then the air partly exhausted, the hand will be firmly pressed to the cylinder because of the air pressure in the room.

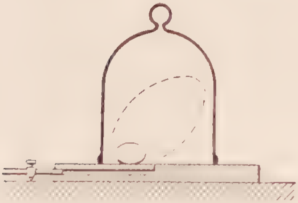

FIG. 67.

If a sealed rubber balloon containing a small amount of air is placed under a bell-jar (Fig. 67), and the air is exhausted from the jar, the balloon will swell out. The air pressure on the outside being removed, the air in the balloon expands.

Von Guericke made a large brass globe in halves (Magdeburg hemispheres). The edges of the halves were smoothed, covered with a heavy grease to make the joint air tight, and then pressed together. When the air was exhausted from the globe, a team of horses hitched to each side by means of ropes could not pull the globe apart. You can easily calculate the pull that would have been required, assuming that the globe was two feet in diameter, and that the exhaustion was perfect (Fig. 68).

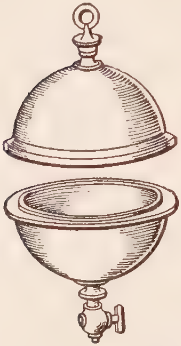

FIG. 68. Magdeburg Hemispheres

What two kinds of air pumps are used? Describe the construction and operation of a bicycle pump. What is the purpose of the leather washer on the piston? What causes the valve in the outlet hose to close after air has passed into the tire? In figure 65 is the valve *V* open or closed when the piston is moving upward? Is valve *V′* open or closed during the upstroke of the piston? Why does air leave the vessel *A*? What limits the degree of vacuum which can be produced by such a pump? Can any pump produce a perfect vacuum? In figure 67 why does the balloon expand when the pump is worked? What are "Magdeburg hemispheres"? Upon what two things would the force necessary to pull them apart depend?

73. Buoyant Force of the Air.—Air, like water, is a fluid and buoys up bodies immersed in it. The buoyant effect is so small, however, that we do not ordinarily notice it. Yet it is there, for Archimedes' principle holds true for air, just as it does for water. A simple experiment will illustrate this buoyant effect of the air. Hang from one end of a short beam balance an incandescent lamp globe. Balance this with weights. Place the apparatus under a bell-jar (receiver) of an air pump, and exhaust a little air.

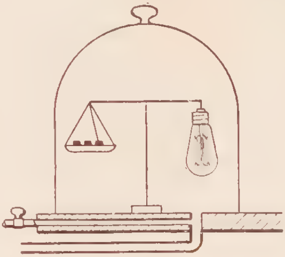

FIG. 69. Lifting Force of Air

The glass globe will descend (Fig. 69). Since the glass globe is much larger than the weights, it is buoyed up more by the air, because it displaces more air. When the air is removed, the real weight of the globe being more than that of the weights, the balance beam goes down. This shows that air buoys up objects, just as water does, and if the object is light enough, it will float in air, just as wood floats on water, and for the same reason. In very delicate weighings it is necessary to make an allowance for this, and the apparent weight in air is corrected for the buoyancy of the weights and also for that of the object which is being weighed.

Fig. 70. Balloon Race

Why does air exert a buoyant force upon bodies in it? What effect does this buoyant force have upon the apparent weight of bodies? How would you obtain the true weight of a body?

74. Balloons.—Hydrogen is a gas that is much lighter than air. A cubic meter of hydrogen weighs only 0.09 kg., while a cubic meter of air weighs 1.29 kg. If, then, a balloon large enough to hold one cubic meter of hydrogen weighs 0.20 kg., the combined weight of the balloon and hydrogen will be 0.29 kg., while the weight of the displaced air will be 1.29 kg.

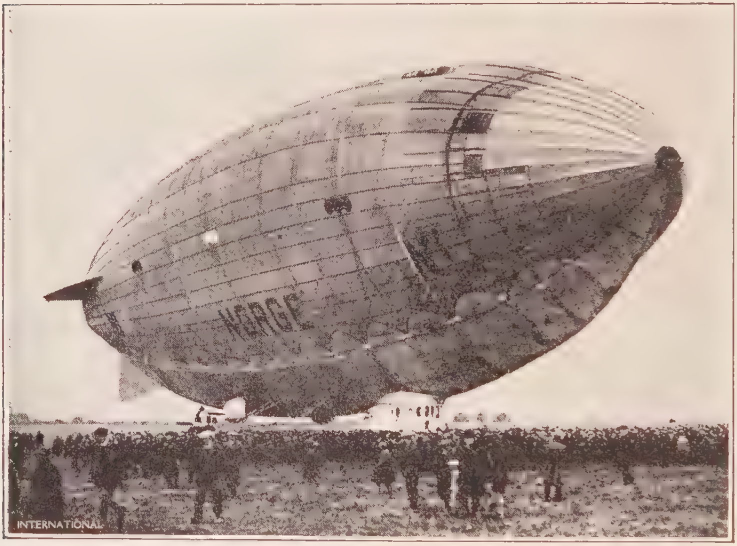

Fig. 71. The Norge, in which Amundsen went to the North Pole in 1924

The balloon will rise, for the same reason that a cork floats on water. Such a balloon would carry a weight of almost 1 kg., and still float. If made large enough, it would have enough lifting power to carry an observer, instruments, and sand ballast (Fig. 70).

Hydrogen is an inflammable gas, and the danger of the balloon catching fire is considerable, especially in observation balloons used in warfare. For that reason, during the World War it was proposed to fill the observation balloons with *helium*, a non-inflammable gas, four times as heavy as hydrogen, but still much lighter than air. The dirigible balloon, the Shenandoah, which was wrecked by a storm, was filled with helium obtained from natural gas wells.

Since air is compressible, it is densest at the bottom, near the surface of the earth. As we go up, the air becomes less dense. At the top of high mountains the air is so thin that it is difficult to breathe. As a balloon rises, the buoyant force of the air upon it becomes less, until there is equilibrium between the weight of the balloon and the weight of the displaced air, and then the balloon floats at a constant level. As the gas slowly escapes through the balloon covering, the balloon displaces less air, and therefore drops. To counteract this, sand ballast is thrown overboard. To descend quickly a large valve in the top of the balloon is opened, gas escapes rapidly, and the balloon comes to earth.

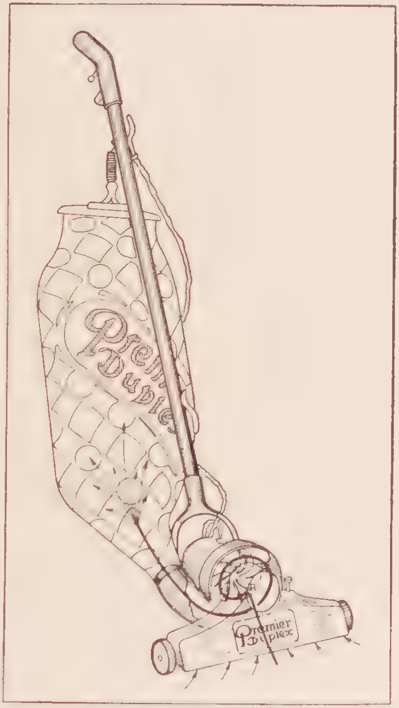

Fig. 72. Vacuum Cleaner. The heavy line indicates the passage of air up through the nozzle, around the fan chamber, and out into the dust bag.

Why does a balloon rise? What limits the height to which it will rise? How does the aviator make it come down? What determines the weight the balloon can lift? What objection is there to the use of hydrogen in balloons? What gas is sometimes used instead?

75. Vacuum Cleaners.—Through the introduction of vacuum cleaners the drudgery of house cleaning has been lessened. These all work by creating a partial vacuum in a slot on the machine. Atmospheric pressure then causes a strong current of air to pass through the narrow slot, and the rapidly moving air carries dust and dirt with it.

The vacuum is usually created by the rapid rotation of a fan, or else by a centrifugal fan pump. The fan acts like an ordinary electric fan, the air being driven forward by the blades, so that a partial vacuum is formed behind the fan. The centrifugal fan pump drives the air toward the ends of the blades, thus producing a partial vacuum at the center of the fan (Fig. 72).

What is a vacuum cleaner? How is the partial vacuum created? What causes the dust to enter the cleaner?

76. Westinghouse Air Brake.—This great safety device, used almost universally by railroads, is operated by compressed air. An air compressor in the engine produces a pressure of about 75 pounds per square inch. A pipe leads from the engine to the brake mechanism mounted under each car. This pipe is made continuous from car to car by coupling the ends together as at c (Fig. 73), so that the engineer can set all of the brakes at once. At V there is an automatic valve. As long as pressure is maintained in the pipe, this valve allows compressed air to pass into the small tank t mounted under the car, but shuts the pipe leading from the air line to the brake cylinder b. As soon,

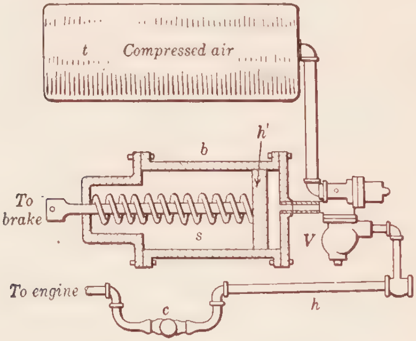

FIG. 73. Westinghouse Air Brake

however, as the air pressure in the pipe *h* drops, either because the engineer opens a valve, or because the train has broken in two, thus opening a coupling, the valve *V* automatically closes the pipe line and opens the connection between the air tank and the brake cylinder. The air pressure on the piston *h′* then forces the brake-shoe against the wheel, and the brake acts. When the engineer again admits air to the pipe *h*, the valve reverses its action, the air in the brake cylinder escapes, the spring *s* forces the brake-shoe away from the wheel, and the brake is released.

What is the purpose of an air brake on a car? What advantages have air brakes over those operated by hand? What happens if the pipe connecting the cars together breaks? Is this an advantage or a disadvantage?

77. The Siphon.—The siphon makes use of atmospheric pressure to transfer a liquid from one level to a lower level over an intervening elevation. A simple form consists of a U-shaped tube, one arm of which is considerably longer than the other (Fig. 74). The tube is filled with water and inverted, with the short arm in the dish of water to be emptied. Water will then flow out of the lower end *D*, until the level of the water in the vessel is below the opening *E*. To explain this action, suppose the end *D* has just been opened, and calculate the pressure in the various parts of the tube. The section *AB* gives at *B* a pressure to the right, equal to the atmospheric pressure, minus the weight of the column of water *AB*. The section *BD* gives a pressure to the left, that equals the atmospheric pressure, minus the weight of the column of water *BD*. The difference between these two pressures equals the

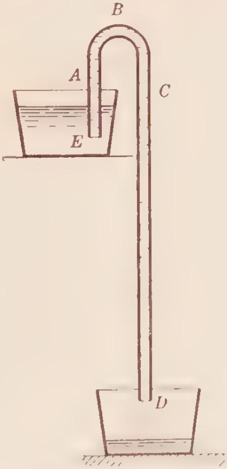

FIG. 74. The Siphon

difference between the weights of the columns *AB* and *BD*, or the weight of the column *CD*. It is this pressure that causes the water to flow. This may also be expressed by saying that the unequal weights of water in the two arms unbalance the atmospheric pressure at the ends of the tube. Evidently, the longer the distance *CD*, the better will the siphon work.

This device is sometimes used to convey water from a spring to a house on the other side of a hill. As it is the pressure of the air on the water that keeps the water in the arm *AB*, and this pressure amounts only to about 15 lb. per sq. in., which can support a column of water about 34 feet high, the siphon will not work over a vertical distance *BC* in excess of 34 feet. In fact, because of air in the water, the practical limit is much less (Fig. 75).

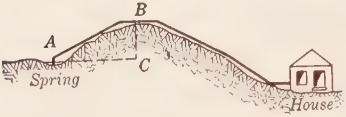

FIG. 75. Siphon Carrying Water over Hill

Describe a siphon. Why does the water flow? Why does one arm have to be longer than the other? What use is made of siphons? Is there a limit to the height over which a siphon will carry water? Why? What is the maximum?

78. The Lift Pump.—This type of pump is often incorrectly spoken of as a suction pump. When you put a straw into a glass of soda and draw through it, it is commonly said that you "suck the soda up." What happens is that you remove part of the air from the straw, thus diminishing the atmospheric pressure inside the straw. The air pressure on the soda then forces the soda up the straw. If the straw were more than 34 feet long and were vertical, you would try in vain to "suck" the soda through it.

The lift pump consists of a pipe *A* (Fig. 76) that dips into water. At the top of this pipe there is a check valve *V*, and over this a cylinder *B*. Inside the cylinder is a closely fitting piston *P*, with a valve *V′* in it. When the piston is raised, it lessens the pressure in the cylinder. The air pressure on the water at *SS* then forces water up the pipe *A* and through the valve *V*. When the piston goes down, this valve *V* closes, and the water passes through the valve *V′* to a position above the piston. When the piston is again raised this water is pushed ahead of it and through the outlet *O*. It is sometimes necessary to prime the pump—that is, to pour a little water into it so as to wet the valves—before it will work.

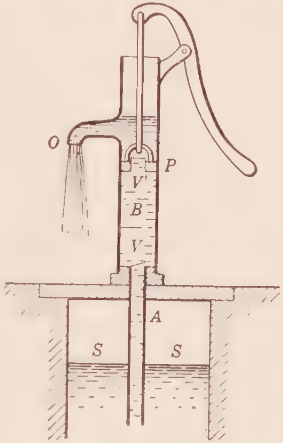

FIG. 76. Lift Pump

The maximum height to which the lift pump will raise water depends, of course, on the atmospheric pressure. At sea level this height is 34 feet or less. The same pump at Denver would not lift the water so high, because Denver is 5200 feet above sea level, and the atmospheric pressure there is much less. (Mean barometric reading in Denver is 24.71 inches.) At the top of the Rocky Mountains, where the elevation is over 14,000 feet, and the barometer stands at about 17.5 inches, the pump would not lift water more than 19.8 feet. When the surface of water in a well is more than 34 feet below the level of the ground, a slightly different type of pump, called a deep-well pump, is used. This has the same mechanism, but the piston rod is made very long, and the piston and valves are placed near the water (Fig. 77).

How is it that you are able to drink soda through a straw? Describe a lift pump. On the up stroke of the piston which valve is open? On the down stroke of the piston what becomes of the water

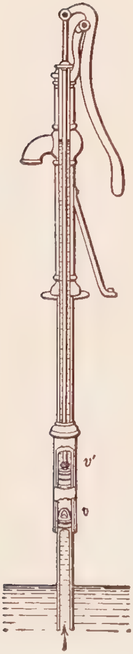

Fig. 77. Deep Well Pump

in the cylinder? Why is this type of pump called a lift pump? Why is it sometimes necessary to prime the pump? What is the real force which causes the water to rise in the pipe? To what maximum height can water be lifted by such a pump? Why can water be lifted higher at New Orleans than at Denver? How is the pump modified to raise water from a deep well?

79. The Force Pump.—This pump is used where it is necessary to force water to a considerable height, as in fighting fires (Fig. 78). It consists of a pipe *A* dipping into the water supply. Above this is a cylinder with a solid piston *P*. When the piston is raised, air pressure forces water up the pipe, past the check valve *V*. When the piston comes down, the valve *V* closes, and the valve *V′* opens, the water flowing into the pipe *B*. The flow of the water is intermittent, gushing out every time the piston comes down.

To maintain a steady flow, an air dome *D* is added. This is simply a reservoir half filled with water. When the water is forced through the pipe *B* by the piston, the air in *D* is compressed. When the piston ceases to force the water in, the air expands and continues to force the water through the pipe, thus causing a continuous flow.

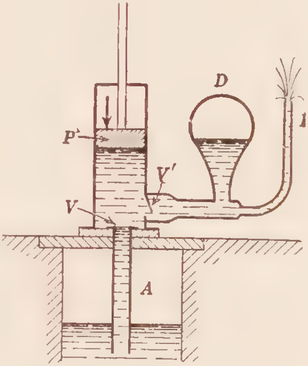

Fig. 78. Force Pump

How does the piston of a force pump differ from that of a lift pump? In figure 78 which way does each valve open? On the upstroke of the piston what happens at valve V? Why is it necessary for this valve to close? On which stroke of the piston does water enter the air dome? What is the purpose of the air dome? To what use is such a pump as this put? What limits the height to which the water can be forced by such a pump?

EXERCISES

1. Describe a simple experiment to show that the air has weight.

2. How would you show that the weight of the air produces a pressure on the surface of the earth?

3. The area of the surface of a human body is 12 sq. ft. or more. What is the total force exerted by the atmosphere on such a body?

4. A block of lead is counterpoised on an equal arm balance by a block of aluminum. Which would appear the heavier: (a) if they are both immersed in water, (b) if the balance and block are placed under a bell-jar and the air exhausted? Explain.

5. Describe the essential parts of the mercury barometer. What determines the height at which the mercury stands? What change would occur in the level of the mercury if the barometer were taken to the bottom of a mine?

6. Of what use are barometers on ships, airplanes, and balloons? Explain your answers.

7. How is the barometer used for weather predictions? What is the underlying principle? What particular fact is it necessary to observe?

8. At a certain place at sea level the day is cloudy, and the barometer (on that day) registers 29.5 in. and is still falling. What are the immediate weather probabilities? Explain.

9. Why is one not conscious of atmospheric pressure? How could you show that there is pressure on the human body?

10. Hydrogen is the lightest gas known. Would it be possible to force enough of it into a steel tank to cause the tank to rise like a balloon? Explain.

11. Why do they use sand as ballast for balloons, and lead or iron for boats?

12. Why is the neck of a balloon always left open? Why does not the gas all escape through the opening?

13. Explain the difference in the causes of the rising of balloons and airplanes.

14. State Boyle's law, and describe an experiment to verify it.

15. Why do air bubbles grow larger as they ascend through water?

16. Fill a bottle with water, and invert it. The water gurgles out instead of running out in a steady stream. Why?

17. At high altitudes it is impossible for men to work hard for any length of time. Explain why.

18. Examine a simple hand bicycle pump and explain the use of each part. Why is there often no valve provided at the outlet?

19. Sketch, describe and explain the simple lift pump. How could you use it to get water from a well 12 feet deep? From a well 40 feet deep? Why is it often necessary to prime a pump?

20. Sketch, describe, and explain the force pump. How would you place it to get water from a well 12 feet deep? From one 40 feet deep? What is the use of the air dome? Explain.

21. What kind of pump is used on the portable tanks used to supply gasoline to automobiles? How may such a pump give short measure?

22. What sort of pump is used to circulate the water in the cooling system of an automobile? Why?

23. What sort of pump is used to circulate the oil in an automobile oiling system? Why?

24. Sketch, describe, and explain the siphon. Mention several practical applications.

25. What determines the velocity of discharge of a siphon? What is the maximum height above the fluid level on the "charge" side? (High level side.) What is the maximum length on the "discharge" side? (Low level side.)

26. What effect has (a) the density of the liquid on the behavior of a siphon? (b) the altitude of the place? (c) the reading of the barometer?

27. Explain one possible cause of the action of intermittent springs.

28. What are the essential differences between a force pump for water, and an air pump such as is used on automobile tires?

29. Five-gallon gasoline cans usually have the spout in one corner of the top. What is the proper way to hold these cans to empty them?

30. A closed barrel of lubricating oil is standing on end. A ¼ inch hole is bored in one stave near the bottom. What do you think will happen? Explain.

31. Sketch, describe and explain the action of the Cartesian diver. State as many laws as you can that are concerned in its action.

PROBLEMS

1. When the barometer reads 76 cm., what would a water barometer read? What is the atmospheric pressure in g. per sq. cm.? In lb. per sq. inch?

2. The original Magdeburg hemispheres had an inside diameter of 22 inches. Assume that the exhaustion was complete. What pull would be required to separate them?

3. What would the barometer reading be at Chicago, 597 ft. above sea level? (For moderate heights 900 ft. elevation causes a drop of 1 inch.)

4. A barometer on an airplane read 27.7 inches, while a barometer on the ground read 29.9 inches. How high was the plane?

5. A diver is working at a depth of 76 ft. What is the density of the air in his suit? Assume that his suit contains 2 cu. ft. of air. If he should be suddenly brought to the surface what volume would the air have?

6. The cylinder of an air pump contains a column of air 20 in. long. The handle (piston) is pushed down with a force of 150 lb. What will be the new length of the air column? (Assume no temperature change.)

7. What change in pressure is necessary to reduce the volume of air in a tank to ¼ of its former volume?

8. The deepest spot yet found in the ocean is 31,600 ft. If a liter of air under atmospheric pressure could be taken to this spot, what would its volume become?

9. A barrel contains 3 ft. of water. How much of this water can be removed by a siphon, if the barrel is on the ground?

10. A jar contains 3 ft. of mercury. How much of this mercury can be removed by a siphon, if the jar is on the ground?

CHAPTER IX

GRAVITATION

80. Weight.—A body on the surface of the earth has weight because there is an attraction between the body and the earth. This attraction is mutual, that is, the earth pulls the body and the body pulls the earth. Since the mass of the body is very, very small, compared to the mass of the earth, the motion of the earth toward the body is so small that we usually neglect it entirely. We must not forget, however, that the action is mutual, and that when you jump from a height to the ground you are pulling the earth to you just as really as the earth is pulling you to it. The weight of a body is the measure of this attractive force, which is called *gravitation.*

Newton discovered that the force of gravitation between two bodies is reduced to one-fourth when the distance between the bodies is doubled, to one-ninth when the distance is trebled, and so on. The law is: **Every particle of matter in the universe attracts every other particle, and the pull between them is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.**

Owing to the shape of the earth, a body weighs more at the poles than at the equator. The mass of the body of course does not change. A body weighs more at sea level than at the top of a high mountain. Since spring balances are used to measure the pull of gravitation, the weight of a body as recorded by a spring balance will differ in different places, but these variations are so small that practically we neglect them.

A beam balance gives the same result wherever it is used, for, if a body weighing one pound is just balanced by a one pound weight in the other pan, and we imagine the balance to be moved to a place where gravity is one tenth less, both the weight and the body to be weighed will lose equally in weight, and the balance will remain in equilibrium. A mass of one pound will always balance a mass of one pound, no matter what the force of gravity, therefore a beam balance can always be used to determine mass.

Why does a body weigh anything? Which pulls harder, the earth or the body being weighed? Explain. Why do bodies fall to the earth instead of the earth's rising to the bodies? Define gravitation. State the law of gravitation. Who discovered and formulated the law of gravitation? Does a body weigh the same all over the earth? Why not? To show that a body weighs less on some parts of the earth than on others would you use a spring balance or a beam balance? Does the mass of a body vary from place to place?

81. Variations of Weight.—A body weighs most at the surface of the earth. If you can imagine a body moved to the center of the earth, it would weigh nothing, for it would be attracted equally in all directions. When a body is raised above the surface of the earth, the distance between its center and the center of the earth is increased, and therefore its weight is diminished. If the body were raised 4,000 miles above the earth, the distance between centers would be doubled, and its weight would be diminished to one fourth of that on the earth.

Does a body weigh most at the surface of the earth, above the surface, or below the surface? Explain. How does weight vary?

82. To Find the Direction in Which Gravity Acts.—Suspend a heavy plumb bob (Fig. 79) by a long string. The plumb bob will point toward the center of the earth, and the direction of the cord will be the direction in which gravity acts. Such a line is called a *vertical* line.

What is a plumb bob? In what direction does a plumb bob point? Define a vertical line.

83. Gravitation Is Universal.—Sun, moon, and stars are made of the same kind of matter as exists on the earth, and gravitation acts on these bodies just as it does on the earth. Sir Isaac Newton, by a study of the motions of the planets, discovered the law controlling their motions, or the law of gravitation, which has already been given. The heavenly bodies are so nearly spherical that we may consider their masses to be concentrated at their centers. The distance between them, then, as used in the law of gravitation, is the distance between their centers.

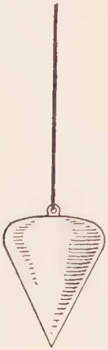
FIG. 79. Plumb Bob

It was by studying the law of gravitation and its effects on the motions of planets that Adams and Leverrier, working independently, discovered, in 1846, the planet Neptune. Certain irregularities had been noticed in the movements of the planets. Adams and Leverrier concluded that these must be due to the existence of some unknown planet. They computed the position that such a body must have to produce these gravitational effects, told the astronomers to point their telescopes at a given time to a certain region of the sky, and so enabled them to discover a new planet.

Does the earth attract the moon? the planet Venus? Is the force of gravitation a universal force? How did a knowledge of the law of gravitation help astronomers to discover Neptune?

84. Center of Gravity.—A uniform rod can rest in a horizontal position if it is supported by a peg through its center, the weights of the two halves balancing about the center. Similarly the beam of a balance is in equilibrium when the weights on the two sides are equal. For any body whatever we can find a point about which the weights of all the particles balance in all positions of the body. This point is called the *center of gravity* of the body. The center of gravity of a body always tends to descend, owing to the attraction of the earth. Hence, when a body is suspended from a peg by a cord, the center of gravity is directly below the peg.

To find the center of gravity of an irregular sheet of cardboard, balance it on the edge of a meter stick and mark the line of contact with the edge. Do the same for a second position of the cardboard on the meter stick. The intersection of the two lines so drawn is the center of gravity (Fig. 80). It is not necessarily a point *in* the body, for if you cut out a circular piece, with *G* as its center, the center of gravity of the card will be at the same point as before. The center of gravity of a wheel is not *in* the wood itself but is at the geometrical center of the wheel.

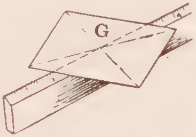

FIG. 80. Finding the Center of Gravity of Cardboard

Define center of gravity. If a body is suspended on a pivot at any place but its center of gravity, what position will the center of gravity take? How would you proceed to find the center of gravity of a board? Where does the center of gravity of a picture frame lie?

85. Stable Equilibrium.—If, when a body is slightly tipped, it tends to return to its former position, it is in *stable equilibrium*. A table or chair is an example. Such a body will have its center of gravity raised by slightly tipping it. If the body is tipped so far that a vertical line through its center of gravity falls outside the base of support, the body will fall, since its center of gravity will seek the lowest point possible (Fig. 81). The greater the distance through which a body can be tipped before this happens, or the larger the base and the lower the center of gravity, the greater is the *stability* of the body. A baby crawling on all fours does not easily fall. When he stands up, his center of gravity is raised, and his base of support lessened, and he falls easily until he learns to balance himself. A boy on stilts has a high center of gravity and a small base of support, and he is therefore likely to fall. Quadrupeds are more stable than bipeds, because of the large base of support included between their four feet.

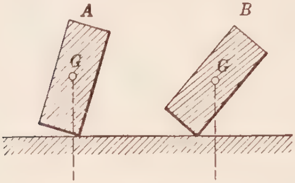

FIG. 81. Stable and Unstable Equilibrium

When is a body in stable equilibrium? What causes it to return to its former position when tipped? What two conditions determine the stability of a body? Why is a four-legged table more stable than a three-legged one?

86. Neutral and Unstable Equilibrium.—If, when a body is slightly tipped, it tends neither to move further, nor to return to its former position, it is in *neutral equilibrium*. A slight motion will neither raise nor lower its center of gravity. A marble on a table, a cone placed on its side, and the wheel of an automobile are examples (Fig. 82).

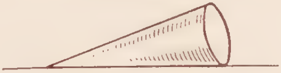

FIG. 82. Neutral Equilibrium

If, when a body is slightly tipped, it tends to continue its motion, it is in *unstable equilibrium*. The tipping lowers its center of gravity. An egg, balanced on its end, is an example.

When is a body in neutral equilibrium? Give an example of a body in neutral equilibrium. When is a body in unstable equilibrium? Explain stable, unstable, and neutral equilibrium by considering the center of gravity.

EXERCISES

1. Why does an empty ship sometimes turn over?

2. Which is the more stable, an empty or a full barrel? Explain.

3. Why does a tight rope walker carry a long rod, with a heavy weight at each end?

4. If the point of a knife blade is thrust into a pencil, the pencil can be balanced as shown in figure 83. Why does it not fall?

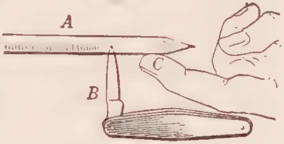

FIG. 83.

5. If two forks are thrust into a cork, and a needle pushed through it, it can be balanced as shown in figure 84*a*. Why does it not fall?

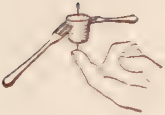

FIG. 84*a*.

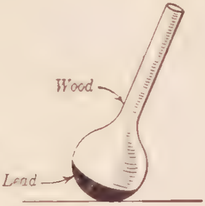

FIG. 84*b*.

6. Which is more stable, a three or a four legged stool?

7. Why does the leaning tower of Pisa not fall?

8. Why does a person carrying a heavy load assume the position shown in figure 85?

9. Why is it impossible to make the toy shown in figure 84*b* remain horizontal?

10. Why is an ordinary "crowned" road, dangerous on a sharp curve?

11. How could you increase the stability of a tall slender vase?

12. Why do very stout men usually have a very erect carriage? Why do very elderly people require a cane?

13. Why do high-heeled shoes decrease the stability of the wearer?

14. Why is it that some sailing ships are never permitted to be completely unloaded? Why do yachts use lead keels?

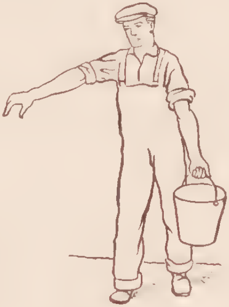

FIG. 85.

15. Why is it difficult to walk on a narrow top edge of a fence?

16. Why is a load of hay more easily upset than a load of stone?

17. How could you find the center of gravity of an irregular object?

18. Make a diagram showing your idea of the correct design for a small ink bottle.

19. What is the peculiarity of design of the salt shakers which will not turn over? What precaution is desirable in filling and using these shakers?

20. Sketch a design for a safe high chair for a baby.

21. What do you mean by weight? Is it a property of matter?

22. What is the difference between weight and mass?

23. Which weighs the more, the earth or a pound of lead?

24. Would a body weigh more on the earth or the moon? Where would it weigh nothing?

25. State the law of gravitation.

26. What daily evidence have we that the moon attracts the earth?

27. Do two apples hanging on a tree attract each other? Explain.

28. Where do bodies weigh more, at the equator or at the poles? Explain. At sea level, or at the top of a high mountain? Explain.

29. Will a plumb-bob hang vertically, if hung from a high precipice by a long line?

PROBLEMS

1. What would happen to the pull between the earth and the moon (a) if the mass of both were doubled? (b) if the mass of the moon were doubled and that of the earth halved? (c) if the distance between the earth and the moon were halved? (d) if it were doubled?

2. The radius of Mars is ½ and its mass ⅑ that of the earth. What would a body weighing 50 lb. on the earth weigh on Mars?

3. If a body could be placed 4000 miles above the earth, how would its weight be changed? What change would its mass undergo?

CHAPTER X

WORK AND ENERGY

87. Work.—From the dictionary we may learn that the word *work* has a great many meanings. In Physics, however, work always means *moving a body by exerting a force,* as in lifting a weight in opposition to the force of gravitation. The columns supporting the heavy weight of a building exert a force but do no work, since there is no motion. When gravity pulls a body to the earth, work is done by the force of gravity. When a body is moved by a force, work is done by the force.

Define work. Do the legs of a table exert forces? Do they do work? Explain. Under what conditions does a force do work?

88. Measuring Work.—To calculate the work done on a body in any case, we must know the magnitude of the force and the distance the body moves. To raise a body that weighs one pound we must exert a force equal to the weight of one pound, and this for brevity we shall call the **force of one pound.** The work done in raising a body of one pound weight one foot is called a **foot-pound.** To raise one hundred pounds ten feet requires, therefore, $100 \times 10 = 1{,}000$ foot-pounds of work.

We sometimes use the kilogram and meter as units, instead of the pound and foot. Our unit of work is then called the **kilogram-meter,** which is the work done in lifting one kilogram a distance of one meter.

We also have to do work against other forces than gravity.

For example, to move a block along a table or a train along a track, we have to overcome the force of friction. Now any force whatever can be stated as equal to a certain number of pounds weight. For instance, to pull a body along a table we may find the necessary force by using a spring balance, for since the spring balance was graduated in pounds by actually using weights, we can obtain the force in pounds by using it. Thus, whatever the direction of the force, **work (in foot-pounds) = force (in pounds weight) × distance (in feet).**

What two things must one know about a force in order to calculate the work it does? What is the unit in which work is measured in the English system? In the metric system? Give the formula by which work is computed.

89. Power.—Work is independent of time. If we lift one pound one foot we have done one foot-pound of work, whether we take one second or one day to lift the weight. Industrially the time taken to do a certain amount of work is of great importance. To include the element of time we use a new term, power. **Power is the time rate of doing work.** The unit in common use is the **horse-power,** which is equal to 33,000 foot-pounds per minute, or, *550 foot-pounds per second.* It was first used by Watt, and was intended to represent the rate at which a strong horse could work steadily. If f is force in pounds, s distance in feet, and t time in seconds, then:

$$\textbf{Horse-power (H.P.)} = \frac{f \times s}{550 \times t}$$

Compare the work done in lifting a book from the floor to a table in one second and in five seconds. If you climb a flight of stairs in three seconds do you do the same amount of work as if you took ten seconds to go up? Explain. Is the same power required in both cases? Explain. Distinguish between work and power. Define power. What is the common unit of power? How much is it in the f.p.s. system?

90. Energy Defined.—Energy is the ability to do work. When we wind a watch spring, our muscular energy is used in doing work, that is, in turning the stem of the watch against the opposition of the spring. When the watch has been wound, the spring has energy, and for 24 hours or more it will turn the wheels of the watch around, move the hands, etc., doing work against friction. Gunpowder has energy, for when ignited it can do work, pushing a bullet out of a gun, or blowing a tree stump out of the ground. The wind, the tides, moving bodies, all have energy, because they can all do work.

Define energy. Give several examples of bodies possessing energy.

91. Kinetic and Potential Energy.—For convenience, energy is classified under two heads. The energy of moving bodies, such as a falling brick, a moving bullet, or the rotating flywheel of a steam engine, is called **kinetic energy**. The energy that a body possesses because of its position as a whole, or the position of its parts, is called **potential energy.** The energy of water in a standpipe; of a compressed spring; of gunpowder; of coal; etc., are examples of potential energy.

What two classes of energy are possessed by bodies? Distinguish between them. Define kinetic energy. Define potential energy. Give two examples of bodies possessing each kind of energy.

92. Measuring Energy.—Since energy is the ability a body has to do work, we measure it by the work the body can do. Thus 100 pounds of water at a height of 10 feet above sea level, if allowed to fall, can do $100 \times 10 = 1{,}000$ foot-pounds of work. Therefore it has 1,000 foot-pounds of potential energy. This is the same thing as saying that the potential energy of the water is equal to the work, 1,000 foot-pounds, required to store up the energy.

To find the potential energy of a stretched spring we must find the number of foot-pounds of work that was required to stretch it. The calculation in this case is not so simple, because the force required to stretch the spring increases as the spring is stretched. In this case we must find the mean force exerted, and this is $\frac{\text{force at start} + \text{force at finish}}{2}$. Since the force at start is zero, the mean force is one half the force at finish. Multiplying this mean force by the distance the spring is stretched, we have the potential energy of the spring in foot-pounds.

The kinetic energy of a body moving with any speed can be measured by finding the work required to give it that speed, or by measuring the work it can do in coming to rest.

A body thrown upward can overcome the force of gravity, that is, its own weight, for a certain distance, and, if we multiply its weight by the distance it rises, we get its kinetic energy at the start. An automobile with the power shut off will run a certain distance against friction. If we multiply the force of friction by the distance which the car moved, we get the kinetic energy of the car when the power was shut off.

Energy is measured in the same units as what other quantity you have studied? How do you find the potential energy of a weight ten feet above the ground? Why does it possess this energy? How did it get it? When it falls will it have less potential energy? Just as it hits the ground, what kind of energy will it have? How much energy will it have? How may the energy of a stretched spring be found? What kind of energy does a moving car have?

93. Energy Is Conserved.—When a body, thrown upward, has risen to its full height, it has lost its kinetic energy, but it now has potential energy, since it can do work in descending. A compressed spring can do work in expanding; it has potential energy because of the relative positions of its parts. The body thrown upward and the expanding spring change the form of their energy, but *the total amount of energy is unchanged* in rising or expanding. This is expressed by saying that the energy is *conserved.*

The case of an automobile, a sled, or a train, moving horizontally against friction, is different, since, when it has stopped, it has no energy of position to start it. Energy expended against friction is subtracted from the sum total of kinetic and potential energy, for it is turned into heat.

When a body is thrown upward, what kind of energy does it have when it starts? When it is half way up? When it is at the top? When it is half way down? When it hits the ground? How does the total amount of energy at one time compare with that at any other time? What becomes of the energy of an automobile when the power is cut off? Is it then available for further use?

94. Transformations of Energy.—When a pendulum is at the extreme point of its swing, it is motionless for an instant. Its energy is then all potential. As it swings down, it moves faster and faster, until, at the lowest point of its swing, its potential energy has all been changed to kinetic energy. It then starts to swing up, the kinetic energy being changed into potential energy, until, when it once more reaches its highest point on the other side, its energy is once more all potential. This change occurs, of course, every time that the pendulum swings from side to side.

When no work is done against frictional forces, there is no change in the sum of kinetic and potential energy. This is the *law of the conservation of energy* as concerns mechanical energy.

What kind of energy has a pendulum at the highest point of its path? At the lowest point of its path? Why does it rise again after reaching its lowest point? State the law of conservation of energy.

95. Perpetual Motion.—A perpetual motion machine would be one that would run forever and do work without the addition of more energy. Such a machine would, of course, be exceedingly useful, and many men have tried to invent one. The law of the conservation of energy shows the impossibility of this scheme, since no machine can move without overcoming friction.

Is a perpetual motion machine possible? Explain your answer. What property would a perpetual motion machine have?

96. Friction.—To push a book along a table top, an effort is required, and the effort is greater the rougher the surface of the table. No matter how smooth the surface may seem to be, it is found, when examined under a microscope, to consist of projections and hollows, and the same is true of the surface of the book. The resistance is due to elevations on one surface bumping against those on the other. **Resistance to the motion of one surface over another is called friction.**

By attaching a spring balance to a heavy block and dragging the block over various surfaces, the force required to move the block can be found. By this means the following statements, sometimes called the **laws of friction,** can be verified:

(1) Friction is independent of speed, if the speed is neither very great nor very small.

(2) Friction is proportional to the force with which the surfaces are pressed together, but it is independent of the areas of the surfaces.

(3) Starting friction is greater than sliding friction.

(4) Friction varies with the materials and the state of the surfaces.

The ratio of the force required to overcome friction to the force with which the surfaces are pressed together is called the coefficient of friction between the surfaces.

$$\text{Coefficient of friction} = \frac{\text{Force to overcome friction}}{\text{Perpendicular pressure between surfaces}}$$

97. Rolling Friction.—If a heavy, polished, cylindrical block of iron is dragged over a surface, first on end, and then rolling on its side, it will be found to roll much more easily than it slides. Rolling friction is less than sliding friction. A locomotive could not pull freight cars if they had to slide on the rails, so the cars are mounted on wheels, and rolling friction substituted for sliding friction.

Why is it difficult to pull a heavy box along the floor? Define friction. Why cannot friction be entirely eliminated? Is the friction lessened by pulling the box more swiftly? More slowly? Will turning the box over onto a wider or narrower side lessen it? Will removing some of the contents of the box make it easier to pull it? Will waxing the floor make it easier? Will putting rollers under it make it easier? Define coefficient of friction.

98. How Friction Is Reduced.—In the moving parts of machinery it is necessary to reduce friction as much as possible. A piston in an automobile engine moves up and down in the cylinder many times per second. To reduce the friction, the surfaces are first made as smooth as possible, and then a film of oil is kept between them. The oil fills up the small pits in the surfaces, so that the motion is one of floating, rather than of sliding. In freight cars the axle passes through a hole in a block attached to the car, and the end of the axle (the bearing) is kept covered with oil. If the supply of oil fails, friction soon heats the bearing, the axle sticks, and we have a "hot box." It is then necessary to stop the train, cool the bearing, and replenish the oil.

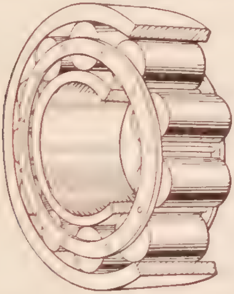

Fig. 86. Roller Bearing

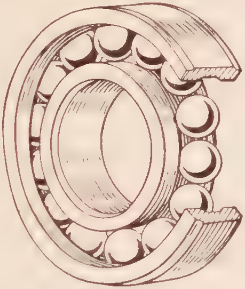

Fig. 87. Ball Bearing

To reduce friction still further we use roller bearings (Fig. 86), so that rolling friction replaces sliding friction. With ball bearings the load is carried on rolling balls (Fig. 87). These are used extensively in bicycles and automobiles.

Why is it desirable to reduce friction in machinery? How is the friction reduced? Why does oil reduce the friction? Why does an unoiled bearing get hot? What advantage has a roller bearing or a ball bearing?

99. Advantages of Friction.—Friction is not always a disadvantage. If it were not for the friction between your shoes and the ground, you could not walk, and everyone would slide down hill. Chains are used on automobiles in wet weather to increase the friction between the tires and the ground and thus prevent dangerous "skidding." Boxes are held together by the friction between the nails and the wood; without it a box would fall to pieces. A locomotive could not pull a train without friction between the driving wheels and the track. When the track is wet or icy, the driving wheels spin around, and sand must be sprinkled on the track. Without friction, belting could not be used to drive machinery.

Is friction always a disadvantage? Why does an automobile skid? Why is sand sprinkled on a trolley track when it is slippery? Mention several cases where friction is used to advantage.

EXERCISES

1. What is energy? State the law of the conservation of energy.

2. What becomes of the energy of a person who has just walked up stairs? Of one who has just walked down stairs? Of a spring in a clock which has run down?

3. Explain how a common clock utilizes stored energy, and discuss briefly the changes of energy from one form to another.

4. Describe the energy transformation in the operation of a hammer in driving a nail.

5. What is the original source from which we get the energy of our electric lights? Of the energy which runs our trains? Our steamships? Our sailing ships? Explain.

6. Why is a perpetual motion machine impossible?

7. In how many ways does an automobile work when running on a level road? When climbing a hill?

8. Why not have a brake on an auto which would instantly stop the wheels?

9. How is work measured? What is the common unit?

10. What is friction? Is it ever of use, is it ever a hindrance? Explain your answer and illustrate it.

11. Why do we oil machinery? Why do we "tape" the handle of a hammer? What should be the condition of the lining of the brakes of an automobile?

12. Why and when do trolley drivers sand the tracks? Do they ever sand the tracks to help start the car? Why?

13. What is the function of non-skid tires? How do they make driving less dangerous? How do the non-skid chains actually perform their office?

14. Why are roller bearings and ball bearings better than plain bearings?

15. How does a nail actually hold two pieces of wood together? How does a screw?

16. Define the coefficient of friction.

17. Why can a heavy engine pull more than a light one of equal power?

18. Give an example of a force acting without doing work.

19. What do you mean by power? How does it differ from force, from work? What is the horse power?

PROBLEMS

1. How much work is done by a 150 pound man while supporting his weight in a standing position? How much if he also holds a 50 pound bag in his hand?

2. How much work is done when a 150 pound man walks up to the top of a 75 foot building? How much is done if he is carried up in an elevator?

3. A fire engine pumps out a cellar which is 18 feet wide, 40 feet long, and 9 feet deep, and full of water? How much work is done if the engine is three feet above the top level of the cellar?

4. In which case is the more work done, (a) if a 200 pound man climbs to the top of a 50 foot building in 2 minutes, or, (b) if he takes 4 minutes?

5. At what horse power does a boy weighing 125 pounds work who climbs to the top of a 50 foot building in 2 minutes?

6. What is the minimum horse power which will permit a 2000 pound automobile to climb a 10% grade at 30 miles per hour if we make no allowance for friction?

7. If a 20,000 horse power engine will drive a steamship at the rate of 18 miles per hour, what pressure is required to force the ship through the water at that speed?

8. What is the energy of an ounce rifle bullet which leaves the gun at 2000 feet per second?

9. A village requires 100,000 gallons (8 lb. per gal.) of water per hour. If the vertical distance from the supply to the reservoir is 60 feet, find the horse power of the engine that, working continually, is required to pump the water. (Waste work being neglected.)

10. A 22 horse power engine is required to drive an 1850 pound automobile 30 miles per hour. What force is exerted by the engine at this speed?

11. A water fall is 100 feet high and discharges 50,000 gallons of water per minute over its bank. If this energy could all be utilized, what horse power could be produced?

12. An elevator when loaded has an unbalanced weight of 2.5 tons. If this is to be raised to the top of a 60 foot building in 80 seconds, what horse power will be required?

13. A man pushes with a force of 50 pounds against a 2000 pound automobile, and moves it horizontally 20 feet. How much work does he do?

14. A box weighing 100 lb. when placed on a 12 ft. plank one end of which is 3 ft. higher than the other, is found to slide slowly down the incline. Find the amount of friction.

15. What is the energy of a 100 pound weight which has been carried to the top of a 100 foot building in 6 minutes? How much work was required to perform the task? How much force? How much horse power? What would be its energy at the instant of impact if it were permitted to fall to the ground?

CHAPTER XI

SIMPLE MACHINES

100. Machines.—By muscular strength alone, man could never have built the Pyramids of Egypt, nor dug the Panama Canal. Our muscles are too weak, when unaided by machinery, for any except light tasks. To pull a nail, or even break a nut, we need a machine. Machines also enable us to call in the tremendous aid of winds, waterfalls, coal, and gasoline.

Some machines, such as the jackscrews for lifting buildings and the windlass for raising a huge anchor, merely *transfer* mechanical energy. Others, such as the steam engine and the dynamo, *transform* energy, and these will be considered later. All machines for transferring mechanical energy can be dissected into simple parts, called **the simple machines.** These are: the lever, the pulley, the wheel and axle, the inclined plane, the wedge, and the screw. In each a force is applied *to* the machine, and an opposing force is overcome *by* the machine. In our discussion of these machines we shall neglect friction, which, except in the screw and wedge, is usually small.

The force applied to the machine we shall call the *effort*, and denote it by E. The resisting force which the machine overcomes we shall call the *resistance*, and denote it by R.

Why are machines needed? What two things do machines do? Which of these shall we first study? What is a simple machine? Mention six simple machines. In every machine what two forces besides friction must be considered? Shall we take friction into account in our present calculations? Define the terms effort and resistance.

101. Principle of Work.—To enable a machine to do work, we must do work on it. When the hand applies a force of 30 pounds to the end of a crowbar and moves it ½ a foot, it does $30 \times \frac{1}{2} = 15$ foot-pounds of work, and supplies that amount of energy to the machine. If, in any case, the effort E is exerted through a distance D_e, the *input* of energy is $E \times D_e$ foot-pounds. The machine does work against the resistance R. If it overcomes the resistance through the distance D_r, the work the machine does, or the *output* of energy, is $R \times D_r$ foot-pounds. Now machines merely *transfer* and *apply energy*, they do not create any, since no human agency can do that. Hence the energy account of a simple machine is:—

$$\textbf{Input} = \textbf{Output} \quad \text{or} \quad \mathbf{E} \times \mathbf{D_e} = \mathbf{R} \times \mathbf{D_r}$$

From the last equation it follows that:

$$\frac{R}{E} = \frac{D_e}{D_r}$$

If R is greater than E, as when we lift a stone by a crowbar, we get a large force by the exertion of a small one. In that case D_e is greater than D_r and the greater force acts through a smaller distance. Thus we gain force by sacrificing distance, and we are content to do so, when a large force is necessary. We can also do the opposite, that is, by making R less than E, we can gain distance at the expense of force.

What must be done to enable a machine to do work? What is meant by the terms input and output? How is the input computed? The output? How does the input compare with the output? If the resistance is to be larger than the effort, what must be true of the distances through which they move? How can the resistance be exerted through a greater distance than the effort?

102. Mechanical Advantage.—The ratio of resistance to effort is called the *mechanical advantage* of the machine. Thus when we lift a 300-pound stone by exerting a force of

30 pounds, the mechanical advantage is 300/30 = 10. It will be greater or less than one, depending on whether R is greater than E, or E greater than R.

$$\textbf{Mechanical Advantage} = \frac{\textbf{Resistance}}{\textbf{Effort}} = \frac{\mathbf{R}}{\mathbf{E}}$$

From what was stated in the last paragraph, we can also write:

$$\textbf{Mechanical advantage} = \frac{\textbf{Effort distance}}{\textbf{Resistance distance}} = \frac{\mathbf{D_e}}{\mathbf{D_r}}$$

Define the mechanical advantage of a machine. Is it always greater than one? State the formula for computing the mechanical advantage.

103. Levers.—The first machine used by man was probably a lever. There is no race so uncivilized as not to know how to roll a stone by means of a stick. A horizontal rod AB (Fig. 88) supported on the edge F of a triangular block, will enable us to raise a heavy weight R by a downward force E, applied at B. A rod so used is a *lever*. F is called its *fulcrum*, AF and BF its *arms*, AF being the *resistance arm* and BF the *effort arm*.

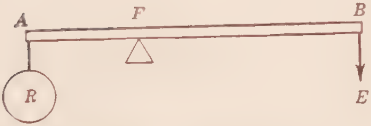

FIG. 88. Lever, showing Effort, Resistance, and Fulcrum

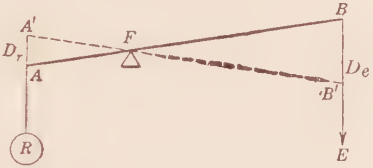

FIG. 89. Law of the Lever

Let B be pressed down a short distance D_e, to B' (Fig. 89), so that A is raised another short distance D_r to A'. The triangles AFA' and BFB' being similar.

$$\frac{BF}{AF} = \frac{D_e}{D_r} = \frac{R}{E} \text{ (see § 102)}$$

and therefore

$$\mathbf{E \times BF = R \times AF}$$

effort × effort arm = resistance × resistance arm

Thus the product, *force* × *lever arm,* is the same for both arms.

In this we have assumed that E and R act in lines which are perpendicular to the lever. This is usually the case. The effort is most effective when it is perpendicular to the lever, and if the resistance were not perpendicular to the lever it would tend to make the lever slip. In other cases we must take, as the lever arm, the perpendicular from the fulcrum on the line in which the force acts. For example, a claw-hammer drawing a nail is a bent lever (Fig. 90), and the resistance arm is the perpendicular, FG, from the fulcrum to the line in which the resistance acts.

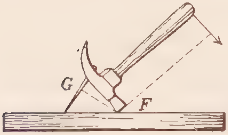

FIG. 90. Bent Lever

What is a lever? Describe a simple lever. What is a fulcrum? The effort arm? The resistance arm? State the mathematical relation existing between the forces and their arms. In what direction should the effort act in order to be most effective? What is a bent lever? Draw a diagram of one.

104. Three Classes of Levers.—Levers are usually divided into three classes, but the principles we have stated apply to all. Levers of the *first class* have the fulcrum between the effort and the resistance (Fig. 91). If the effort arm is longer than the resistance arm, force is gained. A pair of scissors consists of two such levers with the fulcrum at the bolt (Fig. 92). The

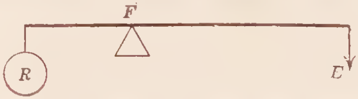

FIG. 91. Lever of the First Class

effort is supplied by the fingers and the resistance by the cloth. If the cloth is hard to cut, we bring it nearer to the fulcrum. For cutting sheet metal, the handle, or effort arm, is made long (tinner's snips, Fig. 93). In these cases the mechanical advantage is greater than unity. When the effort arm is shorter than the resistance arm, speed is gained and the mechanical advantage is less than one.

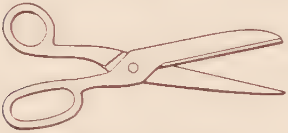

FIG. 92. Scissors

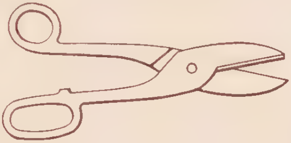

FIG. 93. Tinner's Snips

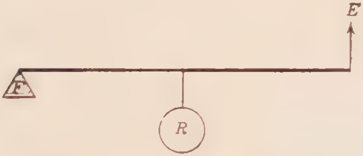

FIG. 94. Lever of the Second Class

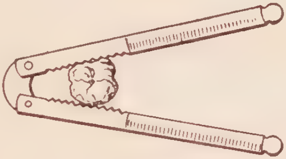

FIG. 95. Nut Cracker

Levers of the *second class* have the resistance between the effort and the fulcrum (Fig. 94) as in nut-crackers. (Fig. 95.) The mechanical advantage is always greater than one.

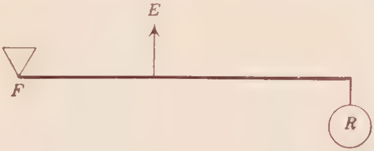

FIG. 96. Lever of the Third Class

Levers of the *third class* have the effort between the fulcrum and the resistance (Fig. 96) as in sugar tongs (Fig. 97), grass cutter (Fig. 98), and the forearm. Speed is gained, and the mechanical advantage is less than one.*

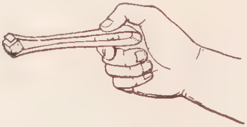

FIG. 97. Sugar Tongs

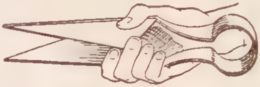

FIG. 98. Grass Cutter

How many classes of levers do we have? What is the relation of the forces and the fulcrum in each? Give an example of each class. To what class does a pair of cutting pliers belong?

105. Balances.—An ordinary beam balance is a lever with equal arms (Fig. 99). By making the beam light and the "knife edges" sharp, the balance can be made so sensitive that the weight of a hair will turn it. Or by making the parts heavy and combining a series of levers, a balance that will weigh a five-ton truck loaded with coal is obtained. A balance is "false" if the fulcrum is to one side of its proper position (Fig. 100). You can easily see how a merchant might profit by putting the weights on one pan of such a balance when buying and on the other when selling.

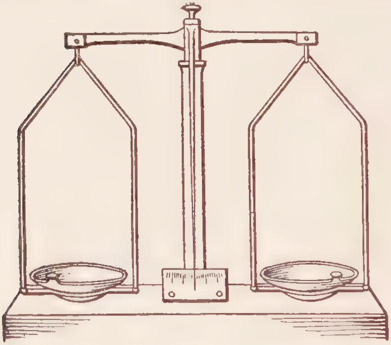

FIG. 99. Beam Balance

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* The order of E, F, R, in the three classes of levers can be remembered from the order of the letters e, f, r, in effort. Thus in the first class the order is E, F, R, in the second F, R, E, and in the third R, E, F.

What kind of machine is a beam balance? In a correct balance, how does the effort compare with the resistance? How does a false balance differ from a correct one?

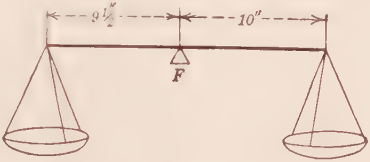

FIG. 100. False Balance

106. The Pulley.—A pulley is a grooved wheel, called a *sheave*, mounted in a frame called the *pulley-block,* so that the sheave can rotate (Fig. 101). A flexible rope passes over the sheave. Often two or more sheaves are mounted in the same pulley-block. As the rope may be quite light, we leave its weight out of account. We also assume that the tension in the rope is everywhere the same.

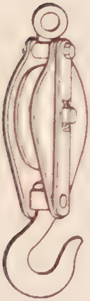

FIG. 101. Pulley and Block

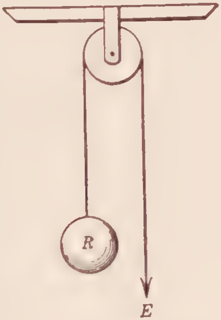

FIG. 102. Single Fixed Pulley

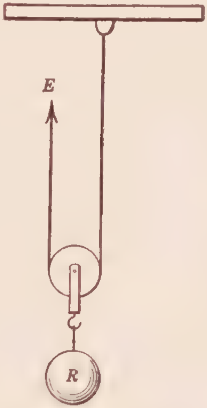

FIG. 103. Single Movable Pulley

When the pulley block is attached to a support the pulley is described as *fixed*. In figure 102 the man pulls *down* and the weight goes *up*. The single fixed pulley is used merely to change the direction of the force. The resistance R is the weight and the effort E is the tension in the rope. Effort and resistance are equal and the mechanical advantage is 1.

When the pulley-block moves or travels with the weight, the pulley is *movable*. In figure 103 for every foot through which the pull acts, the weight rises half a foot. The mechanical advantage is 2.

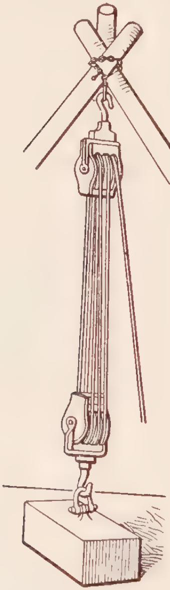

Fig. 104. Commercial Block and Fall

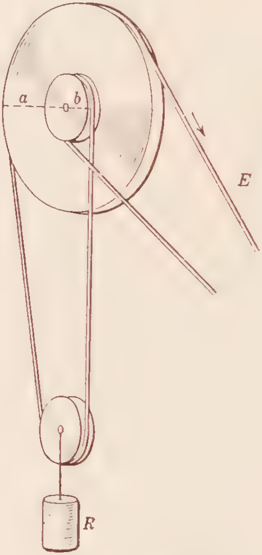

Fig. 105. Differential Pulley

To obtain a large mechanical advantage two pulleys with several sheaves in each block are used. In figure 104 the weight supported is six times the tension in the rope and the mechanical advantage is 6. When the rope is pulled in 6 feet, the weight rises 1 foot.

We can find the mechanical advantage of a system of pulleys, either by noting the number of times the tension of the rope is applied to supporting the weight, or by finding the respective distances that effort and resistance move.

Describe a pulley. What is the sheave? The pulley-block? Distinguish between a fixed and a movable pulley. What is the mechanical advantage of a single fixed pulley? What useful purpose does such a pulley serve? What is the mechanical advantage of a single movable pulley? How can you tell the mechanical advantage of a system of pulleys?

107. **The Differential Pulley** is used when great mechanical advantage is needed, as in automobile repair shops. It consists of an upper block (Fig. 105) with two sheaves of different diameters, fastened together so that they rotate as one, and a lower block with a single sheave. An endless chain runs over the three sheaves. The links of the chain sink into depressions in the sheaves, so that there is no slipping of the chain.

When the chain is pulled down (see arrow), it winds up faster on the larger sheave than it unwinds from the smaller sheave in the upper block, and the weight is slowly raised. The distance through which the effort E acts is much greater than it would be with a single pulley in the upper sheave. The mechanical advantage can be made very great by making a and b nearly equal, the limit being set only by the strength of the chain.

How is a pulley modified to give it a great mechanical advantage? Why does the differential pulley have so great a mechanical advantage? Why is a chain used instead of a rope?

108. **Wheel and Axle.**—From figure 106 it is evident that the wheel and axle is a modification of the lever. It is used in windlasses for cranes, derricks (Fig. 107), and wells (Fig. 108); for the steering wheel of a ship, and in the capstan for raising the anchor (Fig. 109).

A well windlass is shown in figure 108. The fulcrum F is at the center of the axle (shaft), the resistance arm is AC, and the effort arm BF. The resistance is the weight of the bucket of water, and the effort the muscular force of your arm. $E \times FB = R \times AF$. The modified law of the lever can be stated thus:

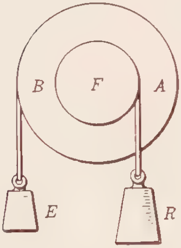

FIG. 106. Principle of Wheel and Axle

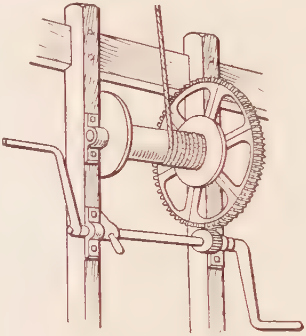

FIG. 107. Windlass of Crane and Derrick

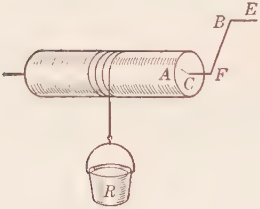

FIG. 108. Windlass of Well

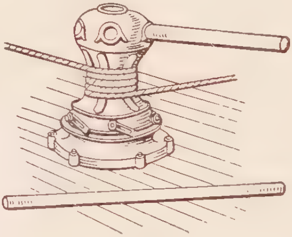

FIG. 109. Capstan of Ship

Effort × radius of circle in which it moves =
resistance × radius of circle in which it moves.

The mechanical advantage is the ratio of the radius of the wheel to the radius of the axle.

Describe a wheel and axle. What other machine does it resemble? What advantage has it over a lever? How is its mechanical advantage measured?

109. The Inclined Plane.—Barrels that are too heavy to be lifted into a wagon may be rolled up planks called *skids*

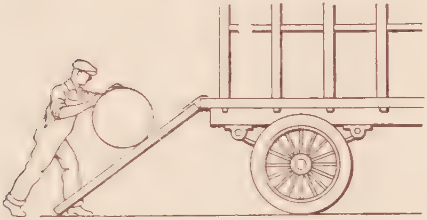

FIG. 110*a*. Wagon Skids

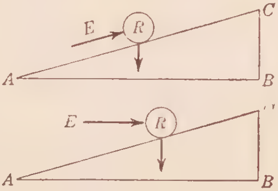

FIG. 110*b*. Inclined Planes

(Fig. 110*a*). Such planks form an *inclined plane*. The resistance R overcome is the weight of the body raised. The effort E may be exerted up the plane or horizontally (Fig. 110*b*).

FIG. 111 A cantilever is a bracket or bent lever and each section of the Forth Bridge (Scotland) is a double bracket, 369 ft. high

When the effort E is parallel to the plane, it acts through a distance AC, and the work it does is $E \times AC$. The weight is a vertical force, and the work done against it must be found from the vertical distance through which the body is raised. It is therefore $R \times BC$. Hence

$$E \times AC = R \times BC$$

or:

Effort × length of plane = resistance × height of plane.

When the effort E is horizontal (parallel to base of plane), it is exerted through a horizontal distance AB, and the work it does is $E \times AB$. The work done against the weight is $R \times BC$, as before. Hence:

$$E \times AB = R \times BC$$

or

Effort × *base of plane* = *resistance* × *height of plane.*

What is an inclined plane? For what kind of use is it adapted? In what two directions may the effort be exerted? How is the total work done against the resistance computed? Give the equation of work done by effort and work done against the resistance for each of the two cases. What is the mechanical advantage in each case? In which case may the effort be smaller?

110. The Screw.—The rotation of a jack-screw can be used to raise a great weight resting on the nut (Fig. 112). The screw is a cylinder on which there is a spiral ridge, called its *thread*. The distance between two consecutive turns of the thread is called the *pitch* of the screw (Fig. 113). We shall denote it by a. In the nut there is a corresponding spiral groove or thread. The thread of the screw may be thought of as a spiral inclined plane (Fig. 111) up which the nut must ascend as the screw turns. For each revolution of the screw the nut must rise a distance equal to the pitch of the screw. If the screw is turned by a lever, of lever arm b, the work done by the effort E in each revolution is $E \times 2\pi b$. In

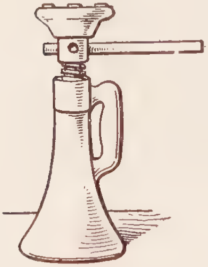
FIG. 112. Jack Screw

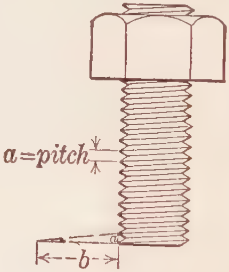

FIG. 113. Screw and Nut

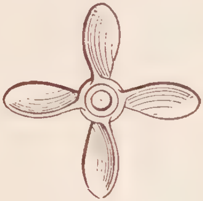
FIG. 114. Ship Propeller

the same time the work done against the resistance is Ra. We must not equate these terms to get the mechanical advantage, since much work is wasted in friction, however well the screw may be lubricated.

Clamps, vises, frames for tennis racquets, etc., use the screw principle to produce great pressure. The propeller of an airplane or of a ship is really a short screw of only one turn. The propeller turns so rapidly that it screws into the air or water, just as a wood screw moves forward into wood (Fig. 114) except that it also hurls the fluid backward.

How may a screw be used to raise a weight? How is the work done against the resistance computed? The work done by the effort? Why is the screw a convenient but very inefficient machine? Mention several applications of the screw.

111. The Wedge consists of two inclined planes (Fig. 115) and the effort is applied parallel to their base. Logs are split by driving wedges into them. An ax used for splitting serves as a wedge. Pins, needles, and nails act on the same principle. The mechanical advantage of the wedge, like that of the screw, is greatly reduced by friction.

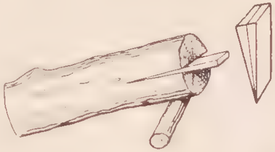

FIG. 115. Wedge Splitting Log

The simple machines can now be regarded as reduced to two in number, for the pulley and wheel and axle can be considered as modification of the lever, and the screw and wedge as variations of the inclined plane.

To what simple machine is the wedge closely related? In what direction is the effort applied? Mention several applications of the wedge. What two simple machines are really the foundation of all simple machines? Show how this is so.

112. Efficiency of Simple Machines.—We use a machine to do some particular work that we wish done, and the work of this kind that it does we call the *useful work* of the machine. Any other work that it may do we call *wasted work*. As there is always some friction in the action of the machine, some work is always wasted.

The ratio of the *useful work*, or the *output*, to the work done on the machine, or the *input*, is called the *efficiency* of the machine.

$$\textbf{Efficiency} = \frac{\textbf{Output}}{\textbf{Input}}$$

In the case of simple machines, when friction is disregarded, input and output are equal, and the efficiency is unity, or, as it is often stated, 100 per cent. An efficiency of 94 per cent means that, of the work done on the machine, 94 per cent is returned by the machine as useful work, while 6 per cent is wasted on friction. There are two of the simple machines, the wedge and the screw, in which the friction is usually large and the efficiency is much less than unity.

Distinguish between useful work and wasted work. Distinguish between input and output. Define efficiency of a machine. What is meant by an efficiency of 94%? Why do not machines have an efficiency of 100%? Which simple machines have a large efficiency and which a small?

EXERCISES

1. What is meant by a simple machine?

2. Explain the "principle of work," and give the fundamental equation.

3. Define mechanical advantage, and explain its importance. Can a machine have a mechanical advantage greater than unity?

4. Draw a diagram and give an illustration of the use of each of the three classes of levers.

5. How could you prove that a beam balance was false?

6. What is the mechanical advantage of a single fixed pulley? Of a single movable pulley?

7. What is the mechanical advantage of a system of pulleys? How is the mechanical advantage found?

8. What has the size of the pulley wheel to do with its mechanical advantage? What effect has it on the efficiency?

9. Of what simple machine is the wheel and axle a development?

10. What is meant by saying "the efficiency of this motor is 72%"? Could the efficiency be 112%?

11. What is the principle of the differential pulley? Is it any better than a combination of pulleys that will give the same mechanical advantage?

PROBLEMS

1. A lever of the first class is 5 feet long. Where must the fulcrum be in order that 150 pounds at one end may balance 25 pounds at the other end? What is the mechanical advantage?

2. A man weighing 125 pounds wishes to lift a 500 pound stone using a 5 foot crowbar. Draw diagrams, showing distances, of two ways in which this may be done.

3. A horse can pull one and two-thirds times as much as a colt. Show by a diagram a method of harnessing which will ensure that each shall pull with proportional force when hitched together to a wagon.

4. How could you harness three horses to a truck so that each must exert the same pull?

5. A coal shovel is 48 inches long. A man holds the shovel with his right hand on the handle at the end, and his left hand 26 inches from that end. If the coal in the shovel weighs 20 pounds and its center of gravity is 5 inches from the edge of the blade what force is exerted by each hand?

6. The effective length of the handle of a pair of tinsmith's snips is 1 foot If a force of 20 pounds is applied at the handle end, what force will be exerted on a piece of sheet iron placed between the jaws of the snips, one half inch from the bolt?

7. Measure an ordinary hammer and calculate the resistance offered by a nail which requires the application of a force of 20 pounds to the hammer's handle before the nail can be pulled out.

8. A pair of nut crackers has handles 8 inches long. If the hand is applied 1.5 inches from the end, with a force of 10 pounds and

the nut is 2 inches from the hinge, what force is applied to break the nut?

9. A wheel-barrow is 6 feet long from the axle to the handle. If a man can lift 100 pounds, how great a weight can he carry in the wheel-barrow, when the load is 2½ feet from the axle? What will be the downward pressure on the axle?

10. A lever of the third class is 10 feet long. If the effort is 5 pounds and the resistance 25 pounds, how far are they apart?

11. The forearm of a man is 14 inches from the center of the hand to the elbow. If the attachment of the lifting muscle is 2 inches above the elbow what force is required to sustain a weight in the hand of 10 pounds, when the forearm is horizontal and at right angles to the upper arm?

12. Draw a diagram of a system of 3 fixed and 3 movable pulleys, showing how they would be arranged to lift a 500 lb. weight. Find the effort that will be required.

13. With a single fixed and a single movable pulley arranged for a downward pull, a man weighing 150 lb. and seated in a boatswain's chair, pulls himself up a mast. What effort must he use?

14. In the last problem, if the man in the chair were pulled up by another man standing on the deck, what effort would be required?

15. A pulley is fastened to the boom of a derrick and another single pulley is fastened to the derrick near the ground. A rope passes through both pulleys. If a horse pulls on one end of the rope with a force of 500 lb., what weight can he lift?

16. A windlass over a well has a diameter of the axle of 6″, the length of the arm of the handle is 15″. What effort is needed to lift a 30 lb. pail of water from the well?

17. A capstan has 6 bars, each 6 ft. long. The diameter of the barrel is 1 ft. What force applied to the ends of the bars simultaneously will lift a 2 ton anchor?

18. Show by a diagram how the wheel and axle is used to operate the small dumbwaiter in apartment houses.

19. A 2 ton truck climbs a 5% grade. Neglecting friction, what pull will be required to move the truck?

20. A 10 ft. plank has one end raised 2 ft. What force applied horizontally will roll a barrel weighing 196 lb. up the incline?

CHAPTER XII

FORCES IN EQUILIBRIUM

113. Force Defined.—*Force is that which produces or tends to produce motion or a change in motion in a body.* When we throw a ball, we must exert force upon it. When a moving trolley is to be stopped, we must exert force to press the brake shoe against the wheels and thus stop their motion. We may exert force without actually causing motion. When you press downward against a table top, no motion is produced. You do, however, *tend to produce motion,* and if the force is increased to a sufficient amount, motion will be produced, and the table top will break.

Define force. Can a force be exerted without producing motion? Illustrate.

114. Equilibrium.—When a number of forces act on a body but do not move it, we say, for brevity, that the forces are *in equilibrium,* that is in a state of balance. Most of the bodies around us are subject to several forces, such as gravity, forces exerted by other bodies, and air pressure, but these forces are in equilibrium. When we say that forces acting on a body are in equilibrium, we do not necessarily mean that the body is at rest. When a locomotive is pulling a train at a constant speed against the friction of the bearings and of the track, air friction, and gravity (if the train is on an upgrade), the forces are in equilibrium. If they were not the speed would be increasing or decreasing. *Forces are in equilibrium when they produce neither motion nor change of motion.*

Define forces in equilibrium. Give two illustrations of such forces. Is the body necessarily at rest? Illustrate.

115. Lines Can Be Used to Represent Forces.—To describe a force fully, we must know its magnitude, its direction, and its point of application. A straight line has three corresponding characteristics—its length, its direction, and the point from which it starts. We may therefore represent forces by straight lines. In drawing diagrams the length of the line is made proportional to the force, its direction that of the force, and its starting point the point of application of the force. The direction of the force is indicated by an arrow on the line.

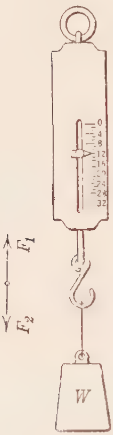

Fig. 116*a*. Two Forces in Equilibrium

What three things must one know about a force? How are these three things represented by a line? In drawing a diagram of forces, what should the relative lengths of the lines be?

116. Two Forces in Equilibrium.—Two equal forces, F_1 and F_2, acting in opposite directions in the same line, produce no motion. They are then described as in *equilibrium.* Thus, when a body hangs from a spring balance, the pull of the balance is equal and opposite to the weight of the body (Fig. 116*a*). When two teams in a tug-of-war exert equal forces, the rope remains at rest. The reader can think of many other examples.

How may two forces be in equilibrium? What is meant by the equilibrium of two forces? Mention several instances of two forces in equilibrium.

117. Three Forces in Equilibrium.—Three forces acting in lines that intersect in a point (concurrent forces) can also be in equilibrium. Arrange three spring balances as shown in figure 116*b*. Denote the forces exerted by them by F_1, F_2, F_3. Any one of these forces just counterbalances the other two acting together, for, if this were not so, the point D would move in some direction, and there would not be equilibrium.

May three forces be in equilibrium? Draw a diagram of three forces in equilibrium.

118. Resultant Force.—In figure 116*b* any two of the forces combined just counterbalance the third. In combination the two must therefore be equivalent to a force that is equal and opposite to the third. This equivalent force is called the *resultant* of the two forces. **The resultant of the two forces is the single force that would produce the same effect as the two forces acting together.**

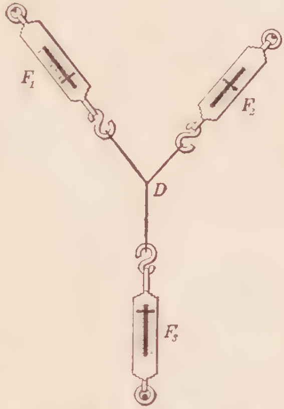

FIG. 116*b*. Three Forces in Equilibrium

Define the resultant of two forces.

119. Parallelogram Law.—A simple geometrical construction enables us to find the resultant of two forces acting at a point. On a sheet of paper draw two lines, OA and OB (Fig. 117*a*), so that the angle between them is equal to the angle between the forces F_1 and F_2 of figure 116*b*, and make the lengths of the lines respectively proportional to the magnitudes of the forces, as indicated by the spring balances. Complete a parallelogram upon these two lines, and draw the diagonal OC from O to the opposite corner. If you measure the length of OC, you will find that, to the scale you have used in laying off OA and OB, the diagonal OC represents a force of the same magnitude as F_3. The force represented by OC is therefore the resultant of F_1 and F_2.

120. Magnitude of Resultant.—The magnitude of the resultant of two forces F_1 and F_2 can be found either by measuring or by calculating the length of the diagonal of the parallelogram (Fig. 117*a*). When the two forces are at right angles (Fig. 117*b*), the parallelogram becomes a rectangle. In that case $(OC)^2 = (OA)^2 + (OB)^2$ or, the resultant F can be found from the equation:

$$F^2 = (F_1)^2 + (F_2)^2$$

When the two forces are not at right angles, you can find the resultant by measuring the length of the diagonal OC. Knowing the scale used, you then know the force represented by the line OC. A solution obtained by drawing a diagram to scale and measuring the length of the resultant is called a *graphic solution.*

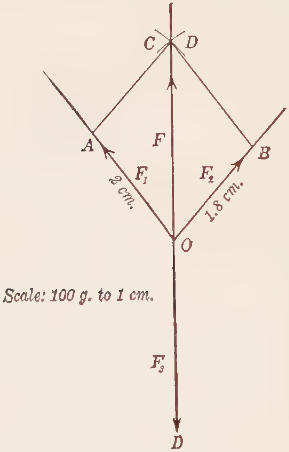

FIG. 117*a*. Parallelogram of Forces

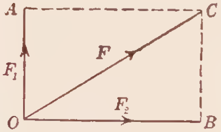

FIG. 117*b*. Magnitude of Resultant

How may the resultant of two forces be found graphically? How is the magnitude of each force represented? How is the magnitude of the resultant represented by the diagonal determined? Under what circumstances could you compute the resultant mathematically? What is meant by the parallelogram of forces?

121. Resolution of a Force into Components.—It must be evident that if two forces can be combined so as to give a single resultant force, we should be able to separate a single force into two forces which would be its equivalent. This reverse process we call the *resolution of forces.* It, also, is performed by drawing a parallelogram, but now the diagonal is given, and the lengths of the sides are required. The force is usually resolved into components at right angles, so that the parallelogram becomes a rectangle.

A familiar case is presented by the ordinary door-catch (Fig. 118*a*). The bolt has an inclined face against which the jamb or frame of the door exerts a force. If the face of the bolt is very smooth, no force parallel to it can be exerted on it. Hence the force F exerted on it is perpendicular to it. Let F be resolved into a component F_1 parallel to the length of the bolt and a component F_2 perpendicular thereto, by drawing a rectangle with AC as diagonal. The component F_2 has no effect, if the bolt is well oiled and slides without friction. F_1 is the effective component, which causes the motion of the bolt.

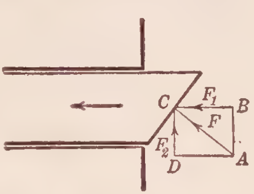

FIG. 118*a*. Door Catch

The principle used in the preceding is of very frequent application. In all such cases the applied force is resolved into two components, one of which is in such a direction that it cannot cause motion. The other is then the effective component. Such applications are common where forces are exerted by fluids.

For example, let us consider how a sailboat is propelled by the wind. The only force that wind can produce on a surface is a force perpendicular to the surface. A wind W, blowing on a sail SS', exerts a force F in the direction AC. Let us now resolve the force F into two components by drawing a rectangle $ABCD$. The component in the direction DC has practically no effect on the motion of the boat, since the keel of the boat prevents motion in that direction. The component in the direction BC, that is, parallel to the keel, is the one that causes the forward motion of the boat. (Fig. 118*b*.)

The resolution of a force into two components also applies to the flight of an airplane. In this case the "wind" is caused by the motion of the airplane. When you are rushing rapidly through still air on a train or automobile, you are meeting the resistance that the air offers because of its inertia, and you feel a wind blowing against you. In figure 119 *PQ* represents a wing of an airplane moving toward the right. The resistance of the air is equivalent to a wind, *W*, blowing toward the left. This exerts a force *F* perpendicular to *PQ*. *F* may be resolved into a component F_1 upward and a component F_2 toward the left. The component F_1, sometimes called the "lift" of the wing, overcomes gravity and supports the weight of the airplane. The component F_2, sometimes called the "drag" of the wing, opposes the forward motion of the airplane, and it has to be overcome by the thrust exerted by the propeller of the airplane. If the "tilt" of the wing is decreased, the force *F* will decrease. There will then be less "drag" and the airplane will move faster. But there will also be less "lift" and the airplane will descend.

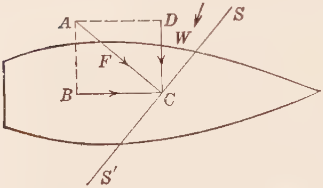

FIG. 118*b*. How the Wind Moves a Sailboat

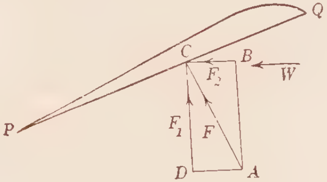

FIG. 119. Airplane Wing

It is not necessary that the two components be at right angles to each other. Suppose we wish to resolve a force F into two components making an angle of 80° with each other. Represent the force by the line *OC* (Fig. 122), and draw from *O* any two lines *OA* and *OB*, making an angle of 80° with

Fig. 120a. Commander Richard E. Byrd's airplane just before he flew to the North Pole and back in 1926

Fig. 120b. Col. Charles A. Lindbergh and the airplane in which he flew from New York to Paris in 1927

each other. Completing the parallelogram gives us the direction and magnitude of the required components. It is evident from the method of construction that, by varying the angle between OA and OC, we can separate the force F into many different pairs of components, and still keep the angle between the components 80°. One example is given in figure 123. The problem is therefore indefinite until the actual direction of one component is given. The graphic method will enable you

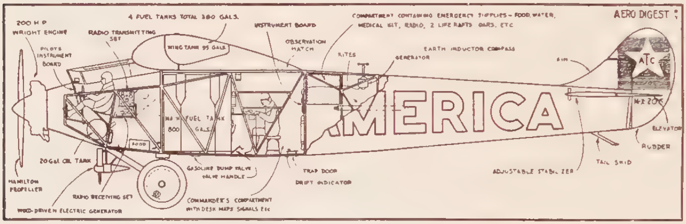

FIG. 121. The airplane in which Commander Richard E. Byrd flew with three companions from New York to France in 1927

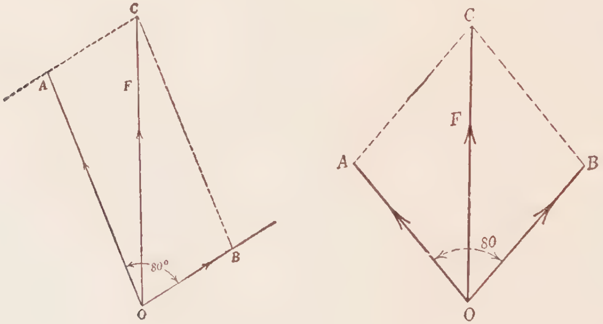

FIG. 122 FIG. 123.

Resolving a Force into Various Pairs of Components to obtain the magnitude of the components in any required case, and, if your drawing is carefully made, their values can be obtained quite closely.

What is meant by the resolution of a force into components? How can this be done graphically? Explain the forces acting in figure 118*a*. Can a force be resolved into components at any angle except a right angle? How many different pairs of components may be found? What must be known in order to solve a problem involving resolution of forces?

122. Forces at Different Points of a Body.—When a body is mounted on an axis it can be held at rest by forces applied at different points. For example, the cylinder mounted on an axis shown in figure 124 is held at rest by two forces. Either, of itself, would produce rotation, but each prevents the rotation that the other would produce.

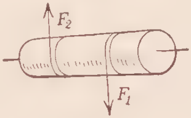

FIG. 124.

Do two forces always have to act at the same point in order to be in equilibrium? Under what condition is it unnecessary?

123. Direction of Rotation.—It is often difficult to describe the rotation of a body. If the top of a flywheel is moving to your right, the bottom is moving to your left. To avoid this difficulty we think of the hands of a clock. If, as we look at a wheel, its direction of rotation is like that of the hands of a clock, we describe the motion as *clockwise;* if the opposite direction, as *counterclockwise.*

What is a clockwise rotation? A counterclockwise rotation? In figure 101 when the effort is applied will the sheaves rotate clockwise or counterclockwise?

124. Moments of Forces.—In the account of the lever, we have seen the importance of the *product of a force by its lever arm.* This product is called the *moment of the force* about the fulcrum. The moment of E in figure 91 tends to rotate the lever in a clockwise direction, while the moment of *R* is counterclockwise. The lever balances when the moments are equal and tend to produce opposite rotations. The same is true of the bent lever (Fig. 90), where the lines of the forces are not parallel.

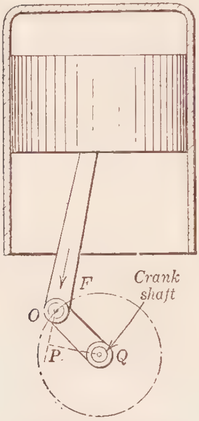

FIG. 125. Moment of Force in Gasoline Engine

Any body mounted on an axis (Fig. 124) is, in principle, a lever. It *remains at rest* when two equal and opposite moments of force act on it, or, if there are several forces, **when the sum of the clockwise moments equals the sum of the counterclockwise moments.**

If the axis on which the body rotates does not pass through the center of gravity (§ 84) of the body, we must reckon in the moment of the weight of the body, treating it as a vertical force acting at the center of gravity.

In all cases we must take care to get the lever arm right. This is always the length of the perpendicular from the axis of rotation on the line of action of the force. Thus, when the piston rod of a gasoline engine is thrusting on the shaft with a force F (Fig. 125), the moment of the force is

$$F \times PQ,$$

PQ being perpendicular to the line of action of F.

What importance attaches to the product of a force and its lever arm? Define moment of a force. When a lever is in equilibrium, what relation exists between the moments of the forces acting upon it? State the law of moments. In what direction must the lever arm always be measured?

125. Parallel Forces.—As an example of parallel forces, suppose a ladder AB of 100 lb. weight and 20 ft. long to be carried by two boys (Fig. 126). If the ladder is uniform, its center of gravity is at its middle point C, and it behaves as if its weight were concentrated there. If each boy carries one end of the ladder, the weight is equally divided between them. Now suppose that one boy holds one end A, while the other boy takes hold at a point B', midway B and C. Denote the load carried by the boy at A by x. That carried by the second boy at B' is $(100-x)$. Consider the moments about A of all the forces. The moment of the force x about A is zero, since its lever arm is zero. The moment of the weight of the ladder about A is (100×10) clockwise. The moment of the force $(100-x)$ about A is $(100-x) \times 15$ counterclockwise. Hence:—

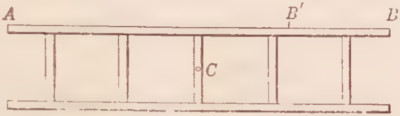

FIG. 126. Parallel Forces

$$100 \times 10 = (100 - x)\ 15$$

$$x = \frac{1500 - 1000}{15} = 33\tfrac{1}{3} \text{ lb.}$$

$$(100 - x) = 66\tfrac{2}{3} \text{ lb.}$$

The same result will be obtained by taking moments about C, B, or B', or about any point.

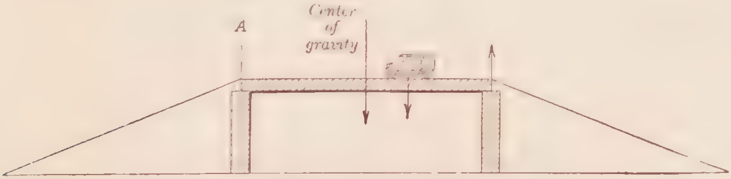

FIG. 127. Parallel Forces

As a slightly more complex case, consider an automobile on a bridge (Fig. 127). To find the weight carried by each pier, we take moments about *any* point, say A. We shall now have two clockwise moments, that of the weight of the bridge and that of the weight of the car, and one counterclockwise moment. We need not consider the reaction of the pier at A because it acts through the point about which the moments are taken. Its moment is therefore zero. The reader should now have no difficulty in completing the calculation.

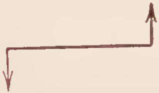

FIG. 128*a*. A Couple

How many forces are acting on the ladder in figure 126? Is the sum of the two upward forces equal to the downward force? If the center of moments is taken at A, what moments are equal? Give the equation of moments using B as the center of moments. In figure 127 how many forces are acting on the bridge? Is it necessary to take the center of moments at any particular place? What should determine your choice?

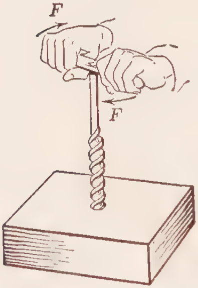

FIG. 128*b*. An Auger Is Turned a Couple

126. Couples.—When two equal parallel forces act at different points of a body, but in opposite directions, they form what is known as a *couple* (Fig. 128*a*). A couple always tends to produce rotation. For example, when a carpenter is using an auger, he is exerting a couple to turn it. (Fig. 128*b*.)

What is meant by a couple? Can a single force successfully oppose a couple?

EXERCISES

1. Define force, work, energy. What is the unit of force? What is the cause of the slight variation in this unit?

2. What are the conditions that make it possible to represent forces by lines? Are lines ever used to represent other magnitudes?

3. What do you mean by forces in equilibrium? Give three illustrations of forces in equilibrium.

4. What do you mean by the resultant of two forces?

5. Define "equilibrant of two forces."

6. Define "moment of a force." What is the fundamental law of moments? What use can be made of this law?

7. Can a single force be resolved into more than two components?

8. Can a single force be resolved into more than two components if the angle between the components is given? Draw diagrams to illustrate the last two questions.

9. Two horses, one on either side of a canal, are pulling a canal boat. The horses are exerting a force of 300 lb. each, and the lines each make an angle of 30° with the direction in which the boat is moving. What is the actual force urging the boat forward?

10. A telegraph pole stands at a right-angled street corner. The wires attached to it stretch south and west. The total pull in each direction is 5000 lb. In what direction should a guy wire be placed to ease this stress and what should be its tension?

11. Two people are carrying a suit case between them. Each is pulling with a force of 30 lb. and the angle between their arms is 60°. What does the suit case weigh?

12. Devise a suit case that will permit two people to carry it between them with a minimum effort.

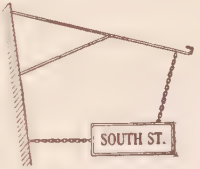

FIG. 129.

13. A street sign is supported by two chains, one horizontal and the other making an angle of 30° with the vertical. (Fig. 129.) The sign weighs 200 lb. What is the tension on the chains?

14. A weight of 200 lb. is supported by two wires, each making an angle of 60° with the vertical. What is the tension in each wire?

15. Four men, each exerting a force of 20 lb., pull horizontally on a rope attached to a wall. What is the tension in the rope?

16. In the last problem, if the men had been opposed by four other men, pulling together in the opposite direction to the first men, what would be the tension in the rope?

17. A toy wagon offers a resistance of 50 lb. to being moved. If the handle makes an angle of 30° with the street, what force must be applied in the direction of the handle to move the wagon?

CHAPTER XIII

MOTION

127. Two Kinds of Motion.—Motion is change of position. Many motions of bodies are complex, as, for example, the "stunts" of an airplane, but they can always be considered as made up of two elementary kinds of motion, *motion in a straight line* and *motion of rotation.* In straight-line (rectilinear) motion all points in a body move equal distances in parallel straight lines. This is the motion of a train on a straight track or of an elevator. In motion of rotation all points in the body move in circles about an axis, as illustrated by a fan or flywheel.

Define motion. Name two kinds of motion. Describe each.

128. All Motion Relative.—Since we have no fixed point in space to which motion can be referred, all motion is relative, that is, it must be stated with reference to some point which is itself in motion. When you walk in a moving train you think of your motion along the floor of the car. The train, however, is moving over the surface of the earth, the earth is rotating on its axis and is also moving around the sun, and the whole solar system is moving through the universe. Absolute motion is therefore unknown, we must always think of the motion of a body as relative to some other body that is itself in motion.

Why is all motion said to be relative? Most motions we study are relative to what body?

129. Motion in a Straight Line.—Straight-line motion may be either uniform or variable. It is uniform in the case of a train that travels twice as far in two seconds as in one second, three times as far in three seconds as in one second, and so on, or, to put it more briefly, when *the distance traveled is proportional to the time.* The distance traveled in every unit of time is called the *velocity* of the body. We denote it by v. If, then, s is the distance traveled in t units of time:

$$s = vt.$$

By means of this equation we can find the value of any one of the quantities in it, if the other two are known.

The units used must always be stated. A velocity of 43 has no meaning, we must say a velocity of 43 ft. per sec., or a velocity of 43 miles per hour.*

Name two kinds of straight-line motion. In uniform motion, what relation always exists between distance traveled and the time? Define velocity. Give a formula which correctly represents the relationship between velocity, time, and space traversed. Explain the necessity of always expressing the units in which the quantities are measured.

130. Composition and Resolution of Velocities.—The motion of a body is sometimes the resultant of two or more separate velocities. A simple case is that of a boat being rowed across a river, while the current is carrying it downstream. If the boat is being rowed at the rate of 4 miles per hour, while the current is carrying it down stream with a velocity of 3 miles per hour, the motion may be represented as in figure 130*a*. The actual path of the boat is represented by the line AC, the length of which is $\sqrt{4^2 + 3^2} = 5$. The boat therefore moves with a *real* or *resultant* velocity of 5 miles per hour, in the direction AC. From this we see that two velocities can be compounded by the parallelogram method, which we used for compounding two forces (§ 119). Evidently, the converse must also be true, that is, we can resolve a velocity into components by constructing a parallelogram, just as a force can be resolved into components (§ 119).

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* It is convenient to remember that a velocity of 1 mile per hour equals a velocity of almost 1½ ft. per sec., or, miles per hour × 1½ = ft. per sec.

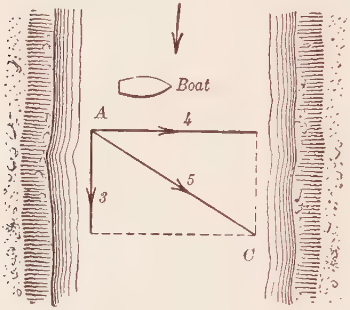


FIG. 130*a*. Composition of Velocities

How can velocities be compounded and resolved into components? Give an illustration of the composition of velocities.

131. Variable Straight-Line Motion.—The velocity of a train is not constant when the train is stopping or starting, and we cannot find the velocity by measuring the distance passed over in a unit of time. But we can observe the distance passed over in a short time by using a stop-watch, and then, by dividing the distance by the time, we can approximate to the velocity. The shorter the time, the better the approximation. We can also think of the velocity at any moment by imagining the motion to become uniform and remain uniform for a unit of time. The distance covered in the unit of time would then be the velocity. The speed-gauge of an automobile or an airplane gives the velocity at any moment by a direct reading. The velocity at any instant equals the distance which would be covered in a unit of time, if the motion remained steady during that time.

132. Acceleration.—The word acceleration may be new to you, but the idea is not. You know what it means to increase your speed in running, and you probably know how the driver of an automobile uses the accelerator to increase the speed, or velocity, as it is more convenient to express rate of motion in scientific work. If the speedometer reads 20 miles per hour at a certain moment and 35 miles per hour 10 seconds later, there was in these 10 seconds an increase of 15 miles per hour in the velocity of the car. This is one way of stating the acceleration of the car. It mentions time *twice*, first in stating the increase in velocity, and next in stating the time required for this increase. The statement is quite clear, but it uses two different units of time, the hour and the second, and we shall find it more convenient to use only feet and seconds (or centimeters and seconds). If we now reduce the increase of velocity to feet per second and then divide by 10 to get the increase per second, we get a more scientific statement of the acceleration, namely, 2.2 ft.-per-sec. per sec.

Acceleration is **rate of increase of velocity.** In the example used the velocity was increasing, and in such cases the acceleration is called a *positive* acceleration. The driver can also retard the car by use of the brakes. A retardation is the same as a *negative* acceleration. For example, if the car referred to was brought back, in 10 seconds, from its velocity of 35 miles per hour to 20 miles per hour, the acceleration was —2.2 ft.-per-sec. per sec.

Is straight line motion always uniform? Illustrate. Is the velocity always the distance passed over in a unit of time? How is the velocity defined when the motion is not uniform? Define acceleration. What is meant by negative acceleration?

133. Uniformly Accelerated Motion.—If a body starts from rest and has at the end of the first second a velocity of 10 ft. per second, at the end of the second second a velocity of 20 ft. per sec., and at the end of the third second a velocity of 30 ft. per sec., its acceleration a is 10 ft.-per-sec. per sec. At the end of t seconds its velocity v is found by

$$v = at$$

Since it started from rest, its velocity was at first zero. At the end of one second it was 10 feet per second, and it had steadily increased from zero to ten. Hence its average velocity was $\frac{0+10}{2} = 5$ ft. per sec. The body traveled as far as if it had been moving for the second with a uniform velocity of 5 ft. per sec. At the end of the second second the velocity was 20 feet per second, and the average velocity in the two seconds was $\frac{0+20}{2} = 10$ ft. per sec., and in the two seconds it traveled $10 \times 2 = 20$ feet. At the end of three seconds its velocity was 30 feet per second, its average velocity in the three seconds was $\frac{0+30}{2} = 15$ ft. per sec., and it traveled $15 \times 3 = 45$ feet, and so on. To put the matter more generally, if the acceleration is a, at the end of t seconds the velocity is at, the average velocity in the t seconds is $\frac{1}{2}\,at$, and the distance s traveled in the t seconds is $\frac{1}{2}\,at \times t$. Hence:

$$s = \tfrac{1}{2}\,at^2$$

A third convenient formula is obtained by getting the value of t from the first equation and putting it in the second. We then have

$$v^2 = 2\,as$$

What is meant by uniformly accelerated motion? How do you find the velocity after a given interval of time? What was the average velocity during the interval? How far did the body travel in the interval? State the formula for these computations. State the formula involving velocity, acceleration, and space traversed.

134. Falling Bodies.—Galileo (1564-1642) realized that the laws of Nature cannot be discovered by simply thinking or talking about them; experiments are necessary. Previous to his time it was thought that a heavy body must fall faster than a light one, because it was heavier. A coin will fall swiftly, but a piece of paper will sink slowly. This, however, is merely a question of air resistance. If the paper be rolled up into a ball, it will fall nearly as fast as the coin. If a coin and a feather be placed in a long tube and the air be removed by an air-pump, they will fall at the same rate.

Galileo had no air-pump and no clock, but, by dropping balls of varying weight from the top of the leaning tower of Pisa, he found that they fell at practically the same rate, with only very slight differences due to air resistance. He also measured the distances that a ball rolled down a long inclined board in equal intervals of time. To get equal intervals of time he weighed the water that escaped from a small hole in the bottom of a keg filled with water (water clock), on the principle that equal amounts of water would escape in equal intervals of time. By this means he discovered the law of falling bodies, and thus laid the foundation stone of modern mechanics. (Fig. 130*b*.)

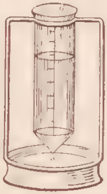


FIG. 130*b*. Galileo's Water Clock

Galileo's discovery, briefly stated, was that a body falling vertically moves with a constant acceleration, and the acceleration is the same for all bodies, if allowance is made for the resistance of the air. The motion of falling bodies can therefore be calculated by means of the formulas of § 133, provided we can find the magnitude of the acceleration.

What was Galileo's discovery regarding falling bodies? How did he make the discovery? What substitute did he use for a clock? Falling bodies have what kind of motion? Will the facts you have learned about uniformly accelerated motion apply to falling bodies?

135. Acceleration of a Falling Body.—The acceleration with which a body falls when entirely unsupported is of great importance, and has been determined with great care. It is denoted by g. It can be found, though not very accurately, by Galileo's method of dropping a body from a building of known height and timing the fall by a stop-watch. Having s and t we can get g from the formula $s = \frac{1}{2} gt^2$.

For the purposes of this book it will be sufficient to take the following values for g.

$g = 980$ *cm.-per-sec. per sec.*
$g = 32.2$ *ft.-per-sec. per sec. (roughly 32 ft.-per-sec. per sec.)*

The formulas for falling bodies, obtained by substituting g for a are:

$$v = gt \qquad s = \tfrac{1}{2} gt^2 \qquad v^2 = 2gs$$

What letter is used to denote the acceleration of falling bodies? How can the acceleration be found experimentally? State the three fundamental formulas for falling bodies.

136. The Pendulum.—Any suspended body, when pushed, starts to swing and is a pendulum. The ideal simple pendulum would be a heavy particle, suspended from an immovable point by a weightless cord. A small iron ball suspended by a long fine wire is very nearly an ideal simple pendulum. The point O (Fig. 131) is called the *center of suspension.* A *single vibration* is the motion from A to C, or from C to A. A *double* or *complete vibration* is the motion from A to C and back to A. The *amplitude* of vibration is one-half the arc of vibration, that is AB or BC.

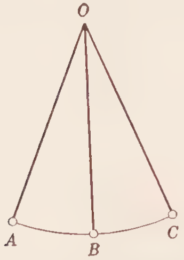


FIG. 131. Simple Pendulum

The time, t, of a single vibration of a simple pendulum of length l can be found by timing a large number of vibrations. It can also be calculated from the following formula, provided the amplitude of vibration is small

$$t = \pi \sqrt{\frac{l}{g}}$$

From this formula we see that the time of vibration is:

(a) *independent of the amplitude of vibration,*

(b) *proportional to the square root of the length,*

(c) *inversely proportional to the square root of the acceleration due to gravity.*

These statements, sometimes called the *laws of the pendulum,* can be tested experimentally. To test the first law, give the pendulum as small an amplitude as can be easily seen, and find the time of 100 vibrations, and then repeat the process but with a somewhat larger amplitude. The times will be the same. To test the second law use a pendulum 100 cm. long and another 25 cm. long. The times will be found to be as 10 to 5. The third law is not so easily tested, but it agrees with experiments made with a pendulum at different places on the earth's surface and on mountain tops, where, as we know from Newton's law of gravitation, the values of g must be different.

From this we see that the pendulum gives us a simple means of finding g at any place. We need only to measure l, find t by timing a large number of vibrations, and then calculate g by the formula.

Define an ideal pendulum. Define the following terms: center of suspension, single vibration, complete vibration, and amplitude. What is the formula for the time of vibration of a pendulum? State the three laws of the pendulum. How can each law be verified? How can the value of g be found with the pendulum?

137. Use of the Pendulum.—The main use of the pendulum is in clocks. The to-and-fro motion of the pendulum bob is used to control the rotary motion of the hands of a clock by means of the escapement. This is a cog wheel, so arranged (Fig. 132) that each vibration of the pendulum allows the cog wheel to move one tooth. The escapement is connected by a train of gears to the hands, and so the hands are moved around. The motion of the pendulum is maintained by means of a weight or a spring. The clock is made to run faster by shortening, or slower by lengthening, the pendulum. Such clocks can be made so accurate that they vary only a few seconds a year. By accurately timing a pendulum of known length, we can find how the magnitude of *g* varies from point to point on the earth. This also tells us how the weight of a body, namely the bob of the pendulum, differs at different places on the earth. This method for finding the variations of weight is much more accurate than a spring balance would be.

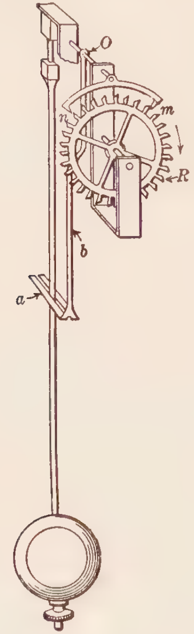


Fig. 132. Clock Escapement

What is the principal use of a pendulum? What purpose does it serve in the clock? Does the pendulum make the clock go? If the clock runs too fast, what should be done?

138. Bodies Thrown Upward.—When a body is thrown vertically upward, its motion is retarded, or we may say that it has a negative acceleration. We can easily find how long it will continue to rise. The velocity it *loses* in every second is what we have denoted by g. Hence if it starts with a velocity of v ft. per sec. and loses g ft. per sec. every sec., it will continue to rise for v/g seconds. Thereafter it falls for the same number of seconds, and reaches the ground with the velocity with which it started. We can now readily find how high it rose, for this is also the distance it had to fall. A body falling for v/g seconds, with an acceleration of g, falls a distance that we obtain by using the general formula $s = \frac{1}{2} gt^2$. In this case s is the height of fall or h, and t is v/g. Hence:

$$h = \frac{v^2}{2g}$$

What kind of motion does a body have when thrown vertically upward? How much velocity does it lose each second? How long will it continue to rise? How long will it fall? How can you find how high it will go?

139. Bodies Thrown Horizontally.—A baseball thrown horizontally does not continue to travel horizontally. It drops while it moves forward, traveling in a downward curved line. This would seem to make the motion complex, but there is one fact that helps us greatly. *The body drops exactly as much in any time as if it had merely been allowed to fall.* This we can verify by experiment. *A* and *B* (Fig. 133) are equal brass weights (any blocks will serve) on a very light rod balanced on an upright *C*. If *A* be shot out *horizontally* by a snap of the finger, at the same instant *B* will drop vertically, and the two weights will be heard to strike the ground at the same time.

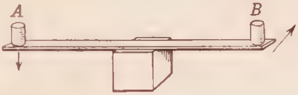


Fig. 133.

The following problem will illustrate the matter. A baseball is thrown horizontally from a height of 8 ft., with a velocity of 100 ft. per sec. Where is it at 0.1, 0.2, 0.3, 0.4, 0.5 second later (Fig. 134*a*)?

At end of 0.1 sec. $s = \frac{1}{2} \cdot 32 \cdot (0.1)^2 = 0.16$ ft.
At end of 0.2 sec. $s = \frac{1}{2} \cdot 32 \cdot (0.2)^2 = 0.64$ ft.
At end of 0.3 sec. $s = \frac{1}{2} \cdot 32 \cdot (0.3)^2 = 1.44$ ft.
At end of 0.4 sec. $s = \frac{1}{2} \cdot 32 \cdot (0.4)^2 = 2.56$ ft.
At end of 0.5 sec. $s = \frac{1}{2} \cdot 32 \cdot (0.5)^2 = 4$ ft.

Does a body thrown horizontally continue to move in that direction? What force acts upon it while it is going? How will the distance it drops in a given time compare with the distance it would drop if it were falling vertically?

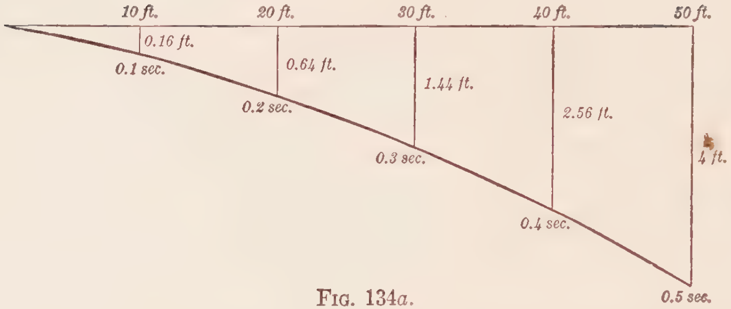


Fig. 134*a*.

140. Resistance of Air.—A sheet of paper, allowed to fall, drops slowly because of air resistance. If crushed into a ball, it falls more rapidly, but not so fast as a coin. A ball or bullet, dropped from a moderate height, say 100 feet, is not appreciably retarded by the air, but a bullet fired at 1000 feet per second is very greatly retarded. The bomb illustrated in Fig. 134*b* took about ½ second longer to reach the ground and traveled about 80 feet less horizontally because of air resistance.

Why does a feather drop more slowly than a stone? Did the bomb in Fig. 134*a* drop vertically? Did the aviator release the bomb when he was over the place he wished to hit? Why?

EXERCISES

1. Define motion, velocity, acceleration.

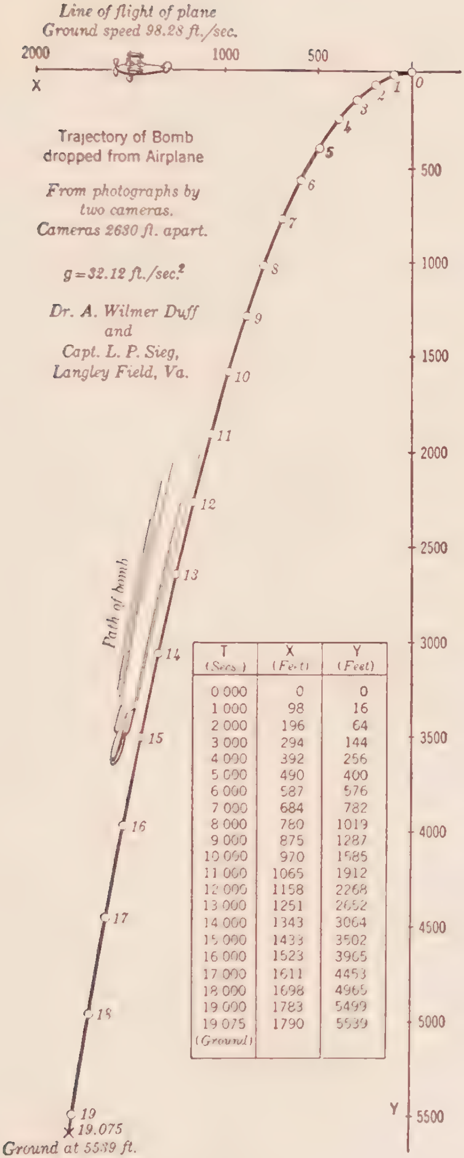
2. What is a constant velocity? A variable velocity?

3. What is the difference between velocity and acceleration?

4. A ball is thrown vertically upward. What is the relation between the time it is rising and the time it is falling?

5. How may a pendulum be used to determine "g"?

6. A ball is dropped twice from the same point inside a trolley car. First when the car is motionless, second when the car has a speed of 30 miles per hour. Will it strike the floor at the same place each time?



Line of flight of plane
Ground speed 98.28 ft./sec.

Trajectory of Bomb
dropped from Airplane

From photographs by
two cameras.
Cameras 2680 ft. apart.

$g = 32.12$ ft./sec.^{2}

Dr. A. Wilmer Duff
and
Capt. L. P. Sieg,
Langley Field, Va.

Ground at 5539 ft.

T *(Secs.)*	X *(Feet)*	Y *(Feet)*
0.000	0	0
1.000	98	16
2.000	196	64
3.000	294	144
4.000	392	256
5.000	490	400
6.000	587	576
7.000	684	782
8.000	780	1019
9.000	875	1287
10.000	970	1585
11.000	1065	1912
12.000	1158	2268
13.000	1251	2652
14.000	1343	3064
15.000	1433	3502
16.000	1523	3965
17.000	1611	4453
18.000	1698	4965
19.000	1783	5499
19.075 *(Ground)*	1790	5539

FIG. 134*b*.

PROBLEMS

1. A man runs 100 yards in 10 sec. What is his speed in miles per hour?

2. A man is walking at the rate of 4 miles per hour. How many feet does he travel per sec.? Per minute?

3. A bomb drops from an airplane at a height of 900 ft. What was its velocity upon reaching the earth?

4. A bullet fired perpendicularly upward (vertically) has a muzzle velocity of 2200 ft. per sec. Neglecting air friction, how high will it rise? How long will it be rising? How long before it returns to the earth?

5. A stone was dropped from a balloon. Two seconds later another stone was dropped. How far will they be apart 5 sec. after the first stone was dropped?

6. In the last problem, if the balloon was 1700 ft. high, will the second stone strike the earth 2 seconds after the first? If not, how much later?

7. A ball was thrown vertically upward and rose 200 ft. What was its initial velocity? Its final velocity? Its time of flight?

8. How far does a falling stone go in the 5th sec. of its fall?

9. A train rolling down hill travels 300 ft. in 10 sec. from rest. How far will it go in half a minute? What will then be its velocity? What is its acceleration?

10. An auto starting from rest with constant acceleration, is going 60 miles per hour in half a minute. How far did it travel in that time?

11. An auto traveling 40 miles per hour is stopped in 110 ft. What is its negative acceleration?

12. A cannon is fired horizontally from the top of a cliff. The projectile traveling 2200 ft. per sec. reaches the plain at a point 2 miles from the base of the cliff. How high is the cliff?

13. An airplane moving horizontally with a speed of 90 miles per hour is 500 ft. high. When directly over his objective, the aviator drops a bomb. By what distance will he miss his target?

CHAPTER XIV

FORCES PRODUCING MOTION

141. Newton's Laws of Motion.—Sir Isaac Newton (1642-1727), who was born in the year in which Galileo died, carried Galileo's work forward and greatly extended it. Newton is best known as the discoverer of the law of gravitation, but he also made many other discoveries in Physics and Mathematics. In particular, he formulated three *Laws of Motion* which have ever since formed the basis of mechanics.

Who was Sir Isaac Newton? In what century did he live? Mention some of his discoveries.

142. Newton's First Law, or, Law of Inertia.—**Every body continues in its state of rest, or of uniform motion in a straight line, unless compelled by some external force to change that state.** A ball pitched along rough ground does not travel far; if started along a smooth road it will go much farther; if started on quite smooth ice it will go a long distance. If there were no force of friction or air resistance to oppose its motion, it would never stop. The stars move, so far as we know, without any resistance, and astronomers tell us that their velocities, sometimes as great as a hundred miles per second, are constant.

All bodies have *inertia*, by which we mean the inability of a body to begin moving or, if it is in motion, its inability to change its motion, without the application of some outside force.

The following is an interesting experiment that you may try at home. Suspend a flatiron by one heavy thread, and from the bottom of the flatiron hang two strands of the same thread (Fig. 135). A slow steady pull on the lower threads will break the single upper strand. A swift jerk will break the two lower threads, before the iron can be set into motion, and the iron will be left suspended.

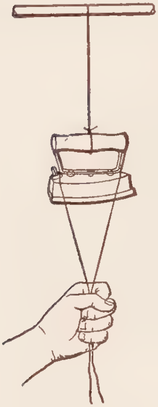


Fig. 135. Illustration of Inertia

Stamping your foot to remove mud or snow, forcing on the head of a hammer by striking the opposite end of the handle against a stone, are common illustrations of inertia. If you jump, facing backwards, from a rapidly moving car, you will certainly fall. When you jump, your body has the rate of motion (velocity) of the car. When your feet touch the ground and come to rest, the remainder of your body continues to move and you fall. If you step off the car, facing forwards, and, as your feet touch the ground, start to run, the velocity of your body will slowly decrease, and you will be safe.

Define inertia. Describe an experiment to illustrate inertia. Why should you face the front when you step from a moving car?

State Newton's first law of motion. Will a moving body keep on going if no force continues to act upon it? Do you know such a case? If the motion of a body changes, what must have caused the change? Why does an automobile come to rest after the engine stops even though the brakes are not applied?

143. Momentum.—It is more difficult to bring a train of cars up to full speed, say 60 miles per hour, than to bring a single car up to the same speed. It is also more difficult to stop the former. To express this, Newton used the phrase "quantity of motion." We now use the term *momentum* for Newton's term, quantity of motion. The momentum of a body of large mass moving with a certain velocity is greater than that of a smaller body moving with the same velocity. To bring a train to a high speed requires more effort than to bring the same train to a lower speed, and it is also more difficult to stop the train in the former case. To take account of both mass and speed, we define momentum as the *product of the mass of a body and the velocity at which the body is moving.* A body of 10 grams mass moving with a velocity of 100 cm. per sec. has 10 × 100 = 1000 units of momentum.

Define momentum. Upon what two things does momentum depend? How is the momentum of a body computed?

144. Newton's Second Law, or, Law of Momentum.—The rate of change of the momentum of a body is proportional to the force that produces it and is in the direction of the force.

By rate of change of momentum we mean change of momentum divided by the time in which the change takes place. For example, suppose a body A of mass m starts from rest and in time t has velocity v (Fig. 136a). In time t its momentum increases from zero to mv. Hence the rate of change of momentum is mv/t. Since v/t is the acceleration a of the body, the rate of change of its momentum is ma. The law states that this is proportional to the force F that produces it.

If A moves without friction, and if the spring gives A a certain momentum in a second, it will give A twice as much momentum per second when stretched so as to exert twice as great a force.

Consider the fall of a mass of 10 grams and that of a mass of 50 grams. The acceleration is the same for both, namely, 980 cm.-per-sec. per sec. The rate of the change of momentum of the first is the value of ma for it, which is 10 × 980. The rate of change of the momentum of the second is 50 × 980. These are in the ratio of 10 to 50, and this is also the ratio of the weights of the

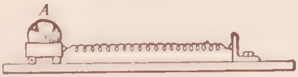


FIG. 136a.

bodies. Hence the weights, which are the forces that cause the motions, are in the same ratio as the rates of change of momentum, which is in agreement with the law.

State Newton's second law. What produces a change of momentum? What is meant by rate of change of momentum? How do you compute the rate of change of momentum?

145. Newton's Third Law, or, Action and Reaction.—Action and reaction are equal and opposite in direction. Newton also stated it thus: **The mutual actions of two bodies are always equal and oppositely directed.**

When you try to describe a force fully, you have to mention *two bodies.* When you press your *hand* against a *wall*, the wall presses back with an equal force. The *earth* attracts a *feather* downward, and the feather pulls the earth upward with an equal force. In such cases it makes no difference which is called the action and which the reaction. When you are on one side of a tug-of-war, you may say that the other side reacts, but they are equally entitled to say that you react. Force is merely a one-sided view of the interaction of two bodies. You cannot exert a force if there is nothing to react. When a pugilist hits the air, he does not exert much force on it, and the reaction is small.

Since the forces that two bodies exert on each other are equal and opposite, they produce equal amounts of momentum. But if the mass of one body is greater than that of the other, the velocity imparted to the first will be less than that imparted to the other. This is illustrated by the experiment shown in figure 136*b*. *A* and *B* are balls of the same size and appearance, but one is a cannonball and the other is of wood. Each pulls on the other by means of the stretched spring. When they are released, it will easily be seen which is the cannonball, because of its smaller velocity. Similarly,

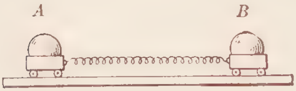


FIG. 136*b*.

when a body is dropped, the earth rises to meet it, but the rise is very minute.

State Newton's third law. What is meant by action and reaction? Can you exert a great force in tearing a piece of tissue paper?

146. Impact.—Suppose a ball of lead, of 100 g. mass, to be moving east with a velocity of 25 cm. per sec., and a second ball, of 20 g. mass, to be moving west with a velocity of 125 cm. per sec. If the two balls met, what will happen? If we multiply the mass of the first ball by its velocity, the product, $100 \times 25 = 2500$, is its momentum. The momentum of the second ball is $20 \times 125 = 2500$. The momentum of the first is equal to that of the second, but they act in opposite directions. When they meet, each will stop the other, and they will come to rest. Their energy of motion will be changed into heat. (Fig. 137.)

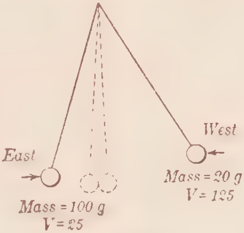


Fig. 137.

If the mass of the second ball had been 100 g., its momentum would have been $100 \times 125 = 12500$. When the balls met, the greater momentum of the second would have overcome the smaller momentum of the first, and the two would have started moving west with a total momentum of $12500 - 2500 = 10000$. Dividing this by 200, the combined mass of the two balls, we get $10000/200 = 50$ cm. per sec. This is their new velocity westward.

In this and similar cases of collision there is *no change in the total momentum of the two bodies*, because the action and reaction between them are equal and opposite and therefore cause equal and opposite changes of momentum, so that the whole momentum remains unchanged.

When two bodies collide, is the momentum of either one changed? If they were going in opposite directions how can you find the resulting momentum? Will their energy be the same after the collision? Explain.

147. Motion in a Circle.—A moving body can be kept rotating in a circle by a force that pulls it toward the center. To whirl a stone attached to a string, the finger must pull on the string. If the string should break, the stone would act as stated in Newton's first law. It would fly off in a straight line, along a tangent to the circle, since that was the direction of its motion when the force ceased to act on it. Mud flies off tangentially from a bicycle or automobile wheel.

The force toward the center necessary to keep a body rotating in a circle is called a *centripetal force.* What is the reaction in this case? The finger feels it, for the string pulls outward on the finger. This outward pull is the reaction of the stone. It is also called the *centrifugal force* of the rotating body. In the case of a train going around a curve, the centrifugal force of the train is exerted against the track, which pushes inward with the centripetal force. (Fig. 138*a*.) In starting to "loop" an airplane has to press with great force against the air beneath its wings (Fig. 138*b*).

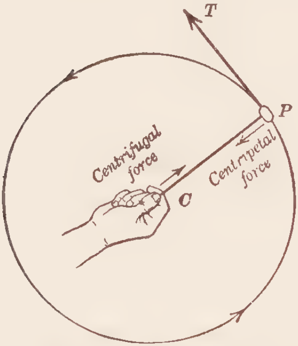


FIG. 138*a*. Motion in a Circle.

Centrifugal force is used in drying clothes, by placing them in a perforated metal cylinder, fitted inside of a larger cylinder. When the inner cylinder is whirled, the water is thrown from the clothes through small holes. The same device is used to separate the sugar syrup from the sugar crystals in the manufacture of sugar. In the centrifugal cream separator the heavier substance (milk) has a greater centrifugal force than the lighter (cream) and therefore gets farther from the center. (Fig. 138*c*.)

Centrifugal forces can also produce disastrous results. An automobile or bicycle, going at too high speed around a curve, will slide outward, the force toward the center (friction) being insufficient to hold it. A train rounding a curve at too high a speed will push outward on the track, thus pulling the rails apart and wrecking the train. To avoid this, the track is banked. A flywheel may burst if the speed is too great: each circumference is stretched until the particles will no longer hold together.

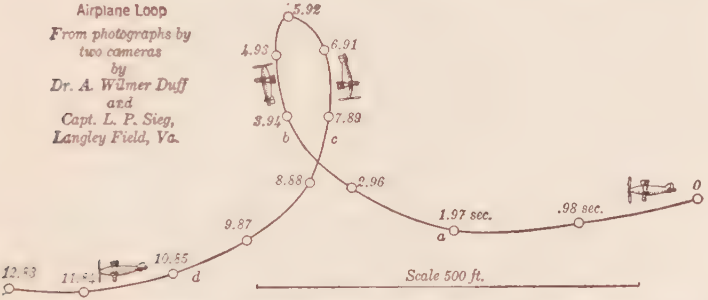


FIG. 138*b*. Centrifugal force causes great strain on the wings of an airplane when "looping," especially where both the speed and the curvature of the path are great, as from *a* to *b* and *c* to *d*. Near the top of the loop the engine is "cut out." The time and the scale of the drawing tell you the whole story. (This is probably the only exact record of a "loop.")

If no force acts on a moving body, in what direction will it move? What is necessary in order to make it move in a circle? What is the force of reaction in this case? Define centrifugal force. Mention two examples of useful centrifugal force. Mention two cases where centrifugal force is a danger.

148. Equation for Second Law of Motion.—By applying the second law of motion we can calculate the acceleration of a body when a known force is applied to it. For example, it applies to finding the acceleration with which a train starts when the locomotive exerts a known pull on the train, and to the negative acceleration or retardation of the train when the brakes apply a known force to stop it. As a simple illustration that will help us to think definitely, suppose that a body is supported with such little friction that we may neglect the friction, while the body is pulled horizontally by a stretched spring (Fig. 136*a*). Let the mass of the body be m, and let the force applied by the spring be F. If the acceleration with which the body starts is a, its rate of change of momentum is ma. Let us now compare this with a case in

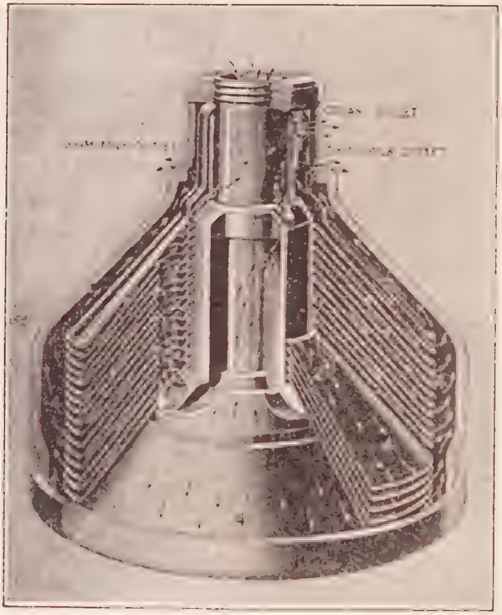


FIG. 138*c*. Milk Separator

which we already know the acceleration. The simplest case is when the same body is allowed to fall. The force acting on it is its weight w, and we know that its acceleration is g. Hence its rate of change of momentum is mg. The second law now tells us that the ratio of F to w is equal to the ratio of ma to mg, and this is evidently the same as the ratio of a to g. Hence

$$\frac{F}{w} = \frac{a}{g}$$

We know the value of g, and if we are given the values of F and w, we can calculate a by means of the equation.

It should be noticed that we have not specified any particular units in which f and w are to be measured. It is only required that they should be in the same units. The ratio of F to w is the same whatever units are used. The same applies to a and g. The only requirement is that they should be in the same units.

The equation is equivalent to saying that *forces applied to a body that is free to move produce accelerations that are in the same ratio as the forces.*

149. Equation in f.p.s. units.*—In our ordinary occupations we are mostly concerned with measurements in feet, pounds, and seconds. Let us now suppose that in the preceding equation F and w are stated in pounds weight, and a and g in ft.-per-sec. per sec. It is then the usual custom to write the equation in the form

$$F = \frac{wa}{g}$$

In this equation F is the force that produces the acceleration a. If the force applied to move the body is opposed by some resistance, such as friction, we must find the net force by subtracting the resistance from the force applied. This will give us F.

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* The use of f.p.s. units in the equation for Newton's second law can be omitted by omitting §§ 149-151. The use of c.g.s. units can be omitted by omitting §§ 153-156.

Example. A body that weighs 100 lb. is drawn over a horizontal surface by a spring balance, and stretches it so that it exerts a force of 40 lb. The resistance of friction is a force of 30 lb. Calculate the acceleration.

The net horizontal force acting on the body in the horizontal direction $40 - 30 = 10$ pounds $= F$. The weight of the body $=$ 100 pounds $= w$. $g = 32.2$ ft.-per-sec. per sec. Substituting these in the above equation we get

$$\frac{10}{100} = \frac{a}{32.2}$$

$$\therefore a = 3.22 \text{ ft.-per-sec. per sec.}$$

150. Kinetic Energy.—The kinetic energy of a body is equal to the work it can do because of its motion. To find the amount of work the body can do, we must let it act against some force, and find how far it will act before the body is brought to rest. Let us suppose a body that weighs w pounds is thrown upward with a velocity v. The force opposing it is its weight, which is w pounds. If it rises to a height s feet the work it does is ws foot-pounds. Now we have seen that a body thrown vertically upward with a velocity v ft. per sec. rises to a height $v^2/2g$ *ft.* Hence the work done by the body, before it is brought to rest, is

$$E = \frac{wv^2}{2g} \text{ foot-pounds.}$$

This is therefore the expression for the kinetic energy of the body in terms of its weight w, and its velocity v.

We have found this expression for kinetic energy by considering what work the moving body could do if its motion were directed upward, but the expression now gives the kinetic energy of the body in whatever direction it may actually be moving.

Example.—An automobile that weighs 1800 lb. is moving with a speed of 25 ft. per sec. What amount of kinetic energy has it?

In this case $w = 1800$ lb., $v = 25$ ft. per sec., and $g = 32.2$ ft.-per-sec. per sec. Hence

$$E = \tfrac{1}{2}\,\frac{1800 \times 25^2}{32.2} = 17{,}469 \text{ ft.-lb.}$$

Define kinetic energy. Explain one method of finding the kinetic energy of a moving body. What is the formula for kinetic energy in terms of weight and velocity?

151. Formula for Centrifugal Force.—It is often necessary to calculate the force required to keep a body rotating in a circle. It is easily seen that the force is greater for a heavy body than for a light one. For instance, a train of empty freight cars can safely go around a curve at a high speed, whereas, if the cars were loaded, the train might push the track outward. The force is also evidently greater the greater the speed. The third factor on which the force depends is the radius of the circle in which the body moves. Anyone who has tried to run an automobile at a high speed around a sharp curve knows that if the radius of the curve is too small, there may not be sufficient friction to keep the car from skidding outward. The formula for calculating F is:

$$F = \frac{w}{g} \times \frac{v^2}{r}$$

where w is the weight of the body in pounds, v the speed, r the radius of the circle, and g is 32 (more accurately 32.2) ft.-per-sec. per sec.

Example. A body having a weight of 10 lb., moving in a circle having a radius of 2 ft., with a velocity of 20 ft. per sec., will give what tension in the cord? Ans. 62.1 foot-pounds.

State the formula by which centrifugal force can be computed.

152. Acceleration toward the Center in Circular Motion.—It will be noticed that the formula for centrifugal motion is the same as that for Newton's second law, except that v^2/r takes the place of a. This means that the force F required for motion in a circle produces an acceleration v^2/r toward the center of the circle. It may be asked: How can there be an acceleration toward the center of the circle when the body never gets nearer to the center? The answer is that, without the acceleration, the body would move along the tangent PT (Fig. 138*a*) and would get farther and farther from the center. When it reached T, its distance from the circle would be CT, and CT would go on increasing at an increasing rate. It can be shown by an independent proof that there is an acceleration v^2/r toward the center when a body revolves with constant speed v in a circle, and when this is proved, the formula for centrifugal force follows from the formula for Newton's second law by substituting v^2/r for a.

ABSOLUTE UNITS

153. Absolute Unit of Force.—The formula given in § 146 is used for calculating forces when we measure things in feet, pounds, and seconds. But these units are not used outside of English-speaking countries, and they are not used in doing advanced work or research work in Physics anywhere. When metric units are used a different formula is more convenient. To explain it, let us go back to Newton's second law. It tells us that, whatever units are used, the force F that is required to give a mass m an acceleration a is *proportional* to ma. It does not say that F is *equal* to ma. However, we can get F equal to ma in all cases if we take a unit of force of suitable size.

An analogy may make this clearer. If a tank is l feet long, m feet broad and n feet deep, its volume v is proportional to lmn. Is v equal to lmn? That depends on what unit of volume we use. The two things are not equal if we are using the gallon as our unit of volume, but they are equal when we use a cubic foot as our unit of volume. This is equivalent to saying that, if v and lmn are to be equal, v must be 1 when l, m, and n are each equal to 1.

Let us now apply similar reasoning to the relation between F and ma. We can write

$$F = ma$$

if we take as our unit of force a force that gives a unit mass (1 g.) unit acceleration (1 cm.-per-sec. per sec.). The unit of force that will satisfy this condition is called the *dyne*. It is equal to *1/980 of the weight of a gram*. To satisfy ourselves about this, let us try it in a case in which we know F, m, and a. Let a body of 1 g. mass fall. Then $m = 1$, and $a = 980$. The force in this case is the weight of a gram, and this is equal to 980 dynes. Substituting in the formula, we get $980 = 1 \times 980$, which is correct. Hence the dyne is the unit of force that we need to make F equal to ma.

154. Centrifugal Force in Absolute Units.—In absolute units, since $F = ma$, and $a = v^2/r$ (§ 152) we have

$$F = \frac{mv^2}{r}$$

where F is in dynes.

Example. A body having a mass of 300 g., moving in a circle having a radius of 40 cm., with a velocity of 50 cm. per sec., will give what tension in the cord?

$$F = \frac{300 \times 50^2}{40} = 19{,}250 \text{ dynes.}$$

State the formulas for circular motion in absolute units.

155. Absolute Unit of Work.—The absolute unit of work is the work done by a force of 1 dyne when it acts through a distance of 1 cm. This is called the *erg*. It is so small that it is convenient, especially in electrical engineering, to use a large multiple of it, 10,000,000 ergs. This is called a *joule*.

What is the absolute unit of work? Define it. Define the joule.

156. Kinetic Energy in Absolute Units.—When a body of m grams mass is thrown upward with a velocity of v cm. per sec. it rises to a height of $v^2/2g$ cm. (see § 138). The force opposing its rise is its weight, which is m grams weight or mg dynes. Hence the work it does against gravity is $mg \times v^2/2g$ ergs. This was therefore the energy with which it started. Hence its kinetic energy at start was

$$E = \frac{mv^2}{2}$$

This gives us the kinetic energy, in ergs, of any body of m grams mass moving with a velocity of v cm. per sec.

Example. A body having a mass of 250 g. and a velocity of 40 cm. per sec., has what kinetic energy?

$$K.E. = \tfrac{1}{2}\ mv^2 = \tfrac{1}{2} \times 250 \times 40^2 = 200{,}000 \text{ ergs.}$$

What absolute unit is used to measure energy? State the formula for kinetic energy in absolute units.

EXERCISES

1. State the three laws of motion.

2. Mention six practical applications of Newton's first law.

3. Which wheels of a wagon are apt to leave the ground in turning a corner too rapidly?

4. Explain the fact that a bullet fired through a window from a position nearby merely drills a hole through the glass, while one fired from a distance shatters the glass.

5. Why does a bicyclist lean inward in turning a corner?

6. Why are grindstones and emery wheels hooded?

7. Why are railroad tracks banked on curves? Which rail is the higher?

8. Explain the action of the centrifugal dryer.

9. Explain the action of the cream separator.

10. What advantage has the underslung automobile body?

11. Why do airplanes tilt the whole machine in order to turn a corner?

12. Why is it dangerous to carry many people on the roof of a bus in wet weather?

13. Why is it dangerous to race an automobile engine in testing it?

14. Why are stationary steam engines always fitted with governors?

15. Draw a diagram and explain the steam engine governor.

16. Why is it difficult to hold the nozzle of the hose of a steam high-pressure fire-engine?

17. Explain just how the propeller of a ship urges the ship forward.

18. Explain the difference between the actions which cause a balloon and an airplane to rise.

19. Why is it dangerous to apply the brake of an automobile too quickly?

20. Why is a "fierce" clutch in an automobile dangerous?

21. There is a man on a canal boat out in the stream, and a man on shore on the dock. There is a cleat on the boat and one on the dock. One rope stretches between. What can the men do to get the boat in as quickly as possible?

22. Why does a gun "kick" when fired?

PROBLEMS

1. A baseball weighs one third of a pound, and it starts from the pitcher's hand with a velocity of 100 ft. per sec. What is its momentum at start?

2. With what kinetic energy did the ball of the preceding problem start?

3. What amount of work did the pitcher do in throwing the ball of the preceding problems?

4. If, in the preceding, the hand of the pitcher moved forward 4 ft. in throwing the ball, what force did he exert on the ball?

5. From the data and results of the preceding problems, calculate the acceleration with which the pitcher's hand moved forward.

6. If you have studied the part on Absolute Units, repeat all the preceding calculations with those units. If all your results have been correct, the time should come out the same.

7. An automobile that weighed 2000 lbs. was brought from rest to a speed of 30 miles per hour in 5 seconds. What force in excess of friction was exerted?

8. If, in the preceding, the power was shut off at the end of the 5 seconds and the car then ran 300 ft. on the horizontal, what was the force of friction?

9. If a 1 oz. bullet leaves a gun with a velocity of 200 ft. per sec., what will be the velocity of the gun if it weighs 4 lb.?

10. Calculate the energy with which the bullet started forward in the preceding and the energy with which the gun started back. Explain why the bullet could have killed a man, but the gunner escaped serious injury.

CHAPTER XV

SOUND

Propagation of Sound

157. Sources of Sound.—Sound is something that comes to the ear and produces the sensation of hearing. The body from which the sound starts, the *source* of the sound, can usually be found without difficulty. By what action does a body emit sound? By striking a small tuning fork, such as musicians use, and holding a match or piece of paper very lightly on it or touching it to the surface of water (Fig. 139), you will find that the tuning fork is in a *state of vibration.* If you strike the tuning fork, and hold it very close to the ear, you will be surprised to find how long it continues to vibrate. A large tuning fork (Fig. 140), against which a light

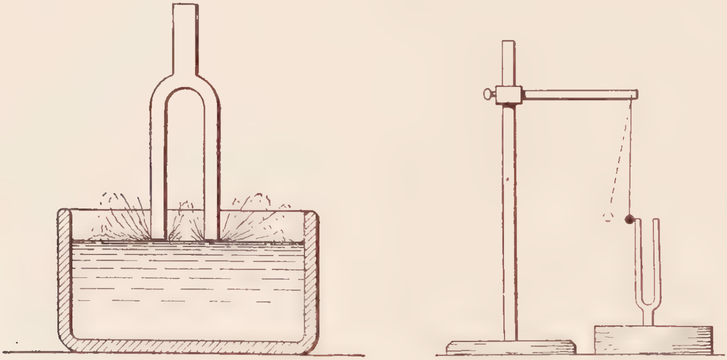

Fig. 139 Fig. 140

Sound Is Due to Vibration

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pendulum (pith ball) hangs, shows the vibrations still more strikingly. In many other cases the vibrations of sounding bodies last but a moment. When a hammer strikes a nail the head of the hammer vibrates for a moment, and so too do the nail and the board into which it is being driven. In all cases **sources of sound are bodies in vibration.**

What is sound? How does a body emit sound? What is the source of all sound?

158. Media in Which Sounds Travel.—Sounds usually come to us through the air. A body may vibrate in a vacuum, but it does not emit sound. This can be shown by pumping the air from a vessel in which an electric bell is sounded, or the following simple method may be used. A small bell hung from the inside of a stopper in a flask can be heard outside when the flask is shaken. Put some water in the flask and boil it. The steam will expel the air. Remove the flame and, at the same moment, push in the stopper (Fig. 141). If the flask be shaken, the sound of the bell will be heard, coming through the steam and through the glass and out into the air. But as the steam condenses and leaves a partial vacuum, the sound dies away, and finally, when the flask is quite cool, little, if any, sound can be heard. We see, then, that sound travels through gases and vapors, but not through a vacuum.

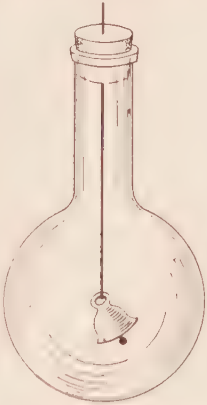

FIG. 141. A Vacuum Does Not Transmit Sound

Sound also travels through solids and liquids. If two stones be struck together under water, a loud sound will be heard by an ear held under the water. A watch placed on one end of a long table can be clearly heard by an ear pressed against the other end of the table. Miners imprisoned by an accident in a mine sometimes send signals to friends outside by blows of a pickax on the rocks. The approach of a distant train or the galloping of horses can be heard by an ear pressed against the ground. The great composer Beethoven, who was deaf, heard some of his own compositions by means of a stick, one end of which rested against the sounding board of a piano, while the other was pressed against his teeth.

Through what does sound usually travel? Can sound travel through a vacuum? Prove your statement. What other things besides air may carry sound? Give examples of sound carried through solids. Through liquids. How did Beethoven partly overcome the handicap of deafness?

159. Velocity of Sound in Air.—Sound takes an appreciable time to travel from the source to the ear. When a man at a distance is seen hammering a nail or chopping a log, the sound of each blow is not heard until some time after the blow is seen. Steam may be observed to issue from a distant steam whistle before the sound is heard. Fire-alarm whistles in different parts of a city are sounded at the same time, but you do not hear them together, if you are not at equal distances from the stations. The sound of thunder starts from a cloud at the same time as a flash of lightning, but the lightning is seen before the thunder is heard. From these facts it is clear that sound requires a considerable time to travel any distance. Its speed is not so great as that of shells from large cannon, for soldiers in the trenches in the World War often heard the sound of a passing shell before the sound of the firing of the gun arrived.

The velocity of sound in air was determined with great care at Paris in 1822 and at Utrecht in 1823. The sounds observed were those of the firing of cannon at great distances. In order to avoid errors due to wind, alternate observations were made with sounds traveling in opposite directions. The mean speed of sound is 344 meters per second, or 1130 feet per second, at 20° C.

A very important point is that *all sounds travel with the same speed*, whatever their pitch or loudness. If they did not, the sound from a band heard at a distance would not be music. The fact that we can hear music at a distance shows that all sounds travel with the same speed.

Does sound travel instantaneously through the air? How do you know? How was the velocity of sound in air first measured? What is the velocity of sound in air at 20° C.? Do two sounds of different pitch travel at the same speed? Prove your answer. By calling more loudly can you make the sound of your voice travel faster?

160. Velocity in Gases.—In different gases at the same pressure and temperature the velocity of sound varies *inversely as the square root of the density*. Thus the density of hydrogen being only $^1/_{16}$ that of oxygen, the velocity of sound in hydrogen is 4 times its velocity in oxygen.

For the same reason, the velocity of sound in any gas increases with rise of temperature, for the density decreases as the temperature rises, if the pressure is constant. The velocity of sound in air increases at the rate of about 2 feet per second per degree Centigrade rise of temperature.

Does sound travel at the same speed in all gases? What two properties of a gas determine the velocity of sound in it? How does an increase in temperature affect the velocity of sound in a gas? How great an increase in velocity is produced if air is heated 1° C.?

161. Velocity in Liquids and Solids.—The velocity of sound in water was first determined in Lake Geneva, Switzerland (Fig. 142), by striking a bell under water, and listening to the sound by means of a funnel-shaped tube held some distance away under water. The velocity of sound in water is 4800 feet per second at 20° C., or about four times the velocity in air. The velocity of sound in solids is still greater.

In iron and steel it is about 16,000 feet per second. This great velocity is due to the very great elasticity of the steel.

How does the velocity of sound in water compare with its velocity in air? Does sound travel rapidly or slowly in steel? Why?

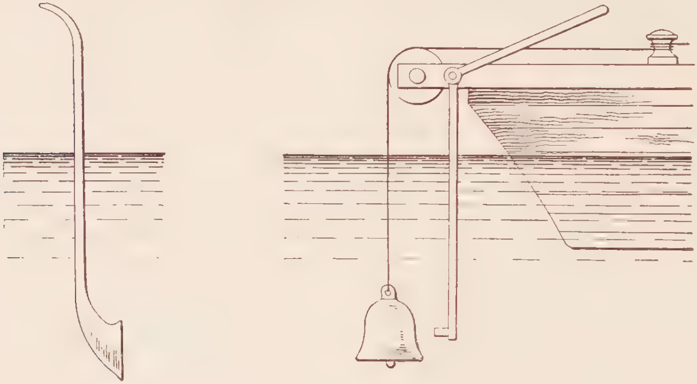

Fig. 142. Determining the Velocity of Sound in Water

162. Nature of Sound.—The energy of a vibrating body is conveyed to the ear by the air or some other medium. It seems evident, therefore, that sound must be a vibration traveling out from the source. The only other possible explanation of sound would be that, like odors, it consists of particles traveling from the source to the ear. But this cannot be the true explanation, for it would be impossible to explain why such particles always traveled with the same speed.

Mention two possible explanations of the nature of sound. What is the accepted explanation?

163. Sensitive Flames.—While the ear is the most sensitive means of detecting sounds, other means are sometimes useful. A long slender flame of illuminating gas (Fig. 143) may be obtained by using, as a burner, a glass tube drawn out to a fine point. If the pressure of the gas is regulated until the flame is just about to "flare" or become unsteady, a sound, especially one of high pitch, will cause the flame to shorten and "roar." A hiss or the rattling of a bunch of keys is especially effective. Such a flame is called a *sensitive flame.*

What is a sensitive flame? Of what use is it?

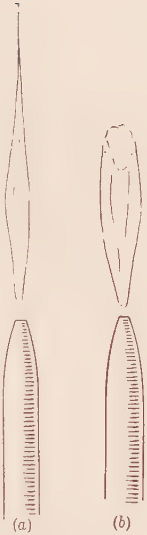

FIG. 143. Sensitive Flames

164. Manometric Flames.—Another useful device for detecting sound is a gas jet, *J*, supplied with gas that passes through a small chamber, one side of which is of thin rubber *R* (Fig. 144). Sound waves falling on *R* produce variations of pressure in the gas, and these cause variations in the height of the flame. The vibrations of the flame are clearly seen by observing them in a rotating mirror *M* (Fig. 145). The image of the flame in the mirror is spread out into a band, the height of which keeps step with the vibrations of the flame. A mouthpiece in the form of a funnel *F* is useful for concentrating the sound on the rubber. Figure 146 shows the result of sounding an organ-pipe at the mouthpiece.

What is a manometric flame? How are variations in the height of the flame made visible?

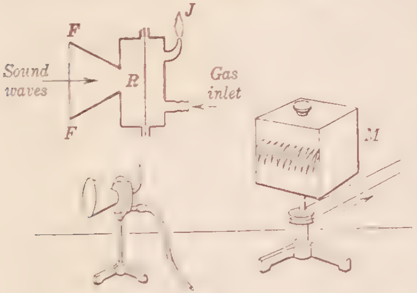

FIG. 144 FIG. 145
Manometric Flame, Capsule, and Mirror

165. Echoes.—It is often observed that a sound, for example a shout, comes back from a distant large surface, such as a side of a barn or a cliff, in the form of an echo. If the observer is traveling parallel to the surface, he can get an echo when he is opposite the obstacle, but not when he is well past it, or, in other words, he must be on a line perpendicular to the surface. The time between the original sound and the echo depends on the observer's distance from the surface. If the total distance to the surface and back is 1130 feet, the echo will come one second after the original sound, since this is the distance sound travels in one second.

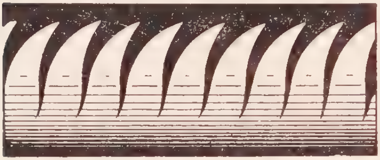

FIG. 146.

An echo is due to *reflection* of sound by a surface. Since the echo of one's own voice is heard only when one is on a line perpendicular to the reflecting surface, it is clear that sound falling perpendicularly on the surface is reflected back along the perpendicular. Echoes of sounds produced at a distance, such as the blowing of a steam whistle, are also familiar. In these cases the observer and the source of sound must be on opposite sides of the perpendicular to the surface, and in such positions that lines from them to the surface make equal angles with the perpendicular (Fig. 147). The rolling of thunder and of the sound of large guns is due to many successive reflections from different obstacles, such as clouds, hills, and forests.

What is an echo? How is it caused? What determines the time between a sound and the echo? What must be a person's position in order to hear the echo of his own voice? What does this show, about the direction of the reflection? What causes the rolling of thunder?

166. Reflection and Refraction of Sound.—From the statements in § 165 we see that when sound is reflected from a surface, the direction of the incident sound and that of the reflected sound make equal angles with the surface. This is also true in the reflection of light, as we shall see later, and of any form of wave motion. This identity of the laws of reflection of sound and of light is well shown by means of a large concave mirror (Fig. 148). A bright light at a distant point P is reflected by the mirror and produces a bright spot at a near point Q. A sound at P, such as the rattling of a bunch of keys, produces a loud sound at Q, as can be shown by placing a sensitive flame so that the end of the burner is at Q, or by holding at Q a small funnel that carries the sound through a rubber tube to the ear.

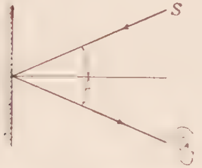

FIG. 147. Cause of Echoes

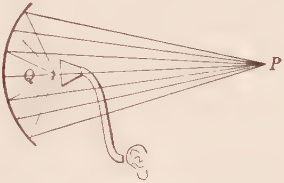

FIG. 148. Reflection of Sound

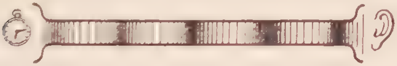

FIG. 149*a*. Speaking Tube

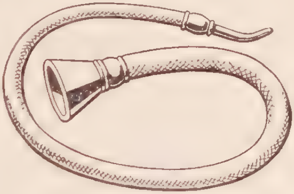

FIG. 149*b*. Ear Trumpet

The curved walls or ceiling of a church or hall often concentrate sound. In the Mormon Tabernacle, at Salt Lake City, a faint sound at one end is often clearly audible near the other end, and a slight rustling may make it difficult to hear the sermon. Smooth stone surfaces are especially good reflectors of sound, as shown by the properties of "whispering galleries." Reflection is taken advantage of in the speaking tube and the ear trumpet (Fig. 149*b*), where sound is concentrated by a cone and transmitted along a tube to the ear. In the megaphone (Fig. 150*a*) sound produced at the small end of a cone is, by reflection, concentrated in the general direction of the axis.

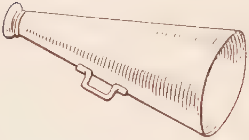

FIG. 150*a*. Megaphone

Rays of sound, like rays of light, are often curved or bent where they pass from one layer of air to another of different density. Sound that starts obliquely upward from a powerful source of sound may finally bend downward and so be heard at great distances, while no sound is heard at points nearer the source. This is the probable cause of "soundless zones" near fog whistles. A notable case occurred during the bombardment of Antwerp in 1914 (Fig. 150*b*). There was a soundless zone between circles of 60 and 90 miles radius. (The crosses show places from which the hearing of sound was reported.) Sound also bends upward when it travels against the wind, so that it is not heard well near the ground at a distance from the source. When it travels with the wind it curves downward and is therefore heard better. All these are cases of refraction of sound, similar to the refraction of light which we shall study later (§ 324).

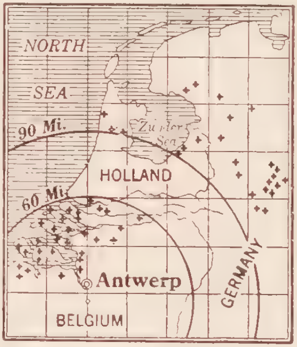

FIG. 150*b*. Soundless Zone at the bombardment of Antwerp in 1914

If you knew the direction of a sound striking a surface, how could you find the direction of the reflected sound? How may sound be concentrated at one spot? Give examples of refraction of sound.

EXERCISES

1. What is sound?

2. How could you prove that a tuning fork was vibrating?

3. What is the state of a body that transmits sound?

4. Can a sound be transmitted through a vacuum? Explain.

5. State some personal experiences of the transmission of sound through substances other than air.

6. How do you know that sound takes time to travel?

7. Which travels faster, high or low notes? How do you know?

8. What is an echo? What is a multiple echo?

9. In what way do pilots coming down a river determine their position by blowing their whistles? Under what circumstances would the method fail?

10. Why do many pulpits have a large curved smooth surface behind the minister?

11. Explain the reason for the usefulness of the speaking tube.

12. Why are sounds much more audible at night? At sea?

13. How do you account for the rolling of thunder?

PROBLEMS

1. The lookout on a steamer's bridge sees the puff of escaping steam from a passing steamer, and $3\frac{1}{2}$ seconds later he hears the sound. What was the distance between the vessels, if the temperature was 10° C.?

2. A heavy flash of lightning is followed by thunder after an interval of $5\frac{1}{2}$ seconds, the temperature being 20° C. How far was the flash from the observer?

3. The captain of a Hudson River steamer hears the echo of his whistle blast 4 seconds after he has sounded the whistle. If the temperature is 18° C., how far is the shore from the steamer?

4. Carbon dioxide is $1\frac{1}{2}$ times as heavy as air. If its elasticity is the same as that of air, what is the velocity of sound in carbon dioxide?

CHAPTER XVI

WAVES

167. Vibrations.—In an earlier section (§ 129) we considered motion in a straight line where the moving body travels steadily forward. Another form of linear motion is to-and-fro motion, such as that of a pendulum bob (Fig. 151), or the up-and-down motion of a weight suspended by a spring (Fig. 152). Such repeated motions are called *vibrations.* If the motion of a pendulum be observed carefully, it will be seen that as the bob starts from A the speed increases to O and then decreases to zero at A', the increase and decrease taking place in the same regular way. The motion of a weight attached to a spring, the motion of the end of a tuning fork, and many other vibrations are of exactly the same kind as that of the bob of the pendulum. Such vibrations are usually called *simple harmonic*

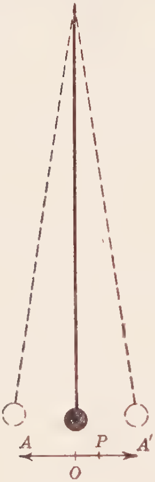

Fig. 151.

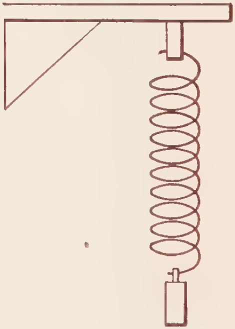

Fig. 152.

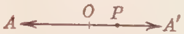

Fig. 153.

Illustrations of Simple Vibrations

motions, but for the sake of brevity we shall call them *simple vibrations*.

The distance a vibrating body, *P*, is from the middle, *O*, of its path of vibration at any moment is called its *displacement*, *OP*, at that moment (Fig. 153). The body is at its greatest displacement when it is at either end, *A* or *A′*, of its path of vibration, and this greatest displacement we call the *amplitude*, *OA*, of the vibration. The whole time in which the body completes one to-and-fro motion is called the *period* of the vibration. It is equal to twice the time from one end of the path to the other.

A pendulum, a swing, a stretched wire, or any elastic body vibrates naturally in a certain period that depends on the properties of the body, such as its length or elasticity. Such vibrations are called *free* or *natural* vibrations. But any such body can be compelled, by using sufficient force, to vibrate in a different period, and such vibrations are called *forced* vibrations. For example, a board on which a wire is stretched (violin) makes forced vibrations when the wire is vibrated. The period of vibration of the board is not its natural period but that of the wire. The board, because of its larger surface, emits a louder sound than the wire alone could.

Describe two forms of linear motion. Define vibrations. When is the speed of a pendulum bob greatest? Define simple harmonic motion. Define simple vibrations. Define displacement of a vibrating body. Define amplitude of a vibration. Period of vibration. What are free vibrations? What are forced vibrations? Give an example of free vibrations and of forced vibrations.

168. Sympathetic Vibrations.—A swing can be started by small impulses, if they are timed properly. Vigorous pulls on the rope are of no avail, if they are applied at random, but slight pulls will set the swing into wide vibrations, if they are timed to agree with the natural or free vibrations of the swing. A large bell, pulled by a rope, is readily started in the same way. A spring diving board, a plank supported at both ends, and even a bridge, can be set into wide vibrations by impulses of the same frequency as the elastic vibrations of the body. For this reason soldiers on the march are directed to "break step" in crossing a light bridge.

Such sympathetic vibrations are of wide occurrence in sound, light, and electric currents. The fundamental principle is the same in all cases: **small impulses produce large vibrations, if they are of the same frequency as the natural vibrations of a body.** From its frequent occurrence in sound this is also called the principle of *resonance.*

How can small forces produce vibrations in a heavy object? Why do soldiers break step in crossing a bridge? Define sympathetic vibrations. Define resonance.

169. Curve Representing a Simple Vibration.—The nature of a simple vibration is best shown by a curve. For example, suppose that, while you are moving the point of a pencil to and fro with a simple vibration in the line AA' on paper, you also draw your hand with a constant speed in a direction perpendicular to AA' (Fig. 154). You will then get a curve that represents a simple vibration. It may be described as a simple vibration spread out.

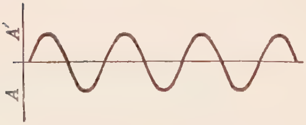

FIG. 154. A Curve Representing a Simple Vibration

A pendulum can be made to draw a similar curve. For this purpose the bob should be in the form of a heavy metal cup, having a small opening at the bottom, and containing fine sand (Fig. 155). If a paper or a board be drawn steadily beneath the pendulum in a direction at right angles to the vibration, the escaping sand will form a curve that represents the vibration.

A tuning fork, with a pointed strip of metal attached to one prong (Fig. 156), will record its vibrations in the form of a curve on lamp-blacked glass, if the point is drawn along the glass.

Such curves are called graphical representations, or, for brevity, *graphs*, of the vibrations.

How can a simple vibration be shown by a graph? How can a pendulum be made to draw its own graph? A tuning fork?

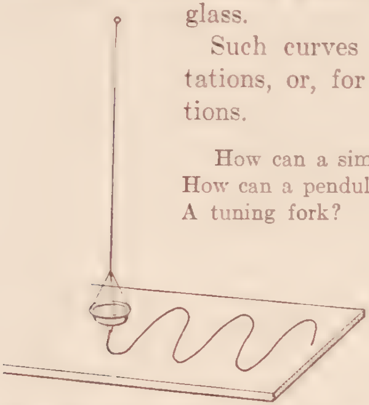

Fig. 155. Sand Pendulum Curve

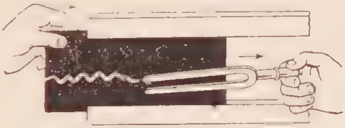

Fig. 156. Tuning Fork

170. Wave Motions, or the Transmission of Vibration.—The waves that are started by dropping a pebble in a pond are ridges and hollows, or crests and troughs, which spread in a circular pattern from the center of disturbance (Fig. 157). The particles of water vibrate about the positions they occupied before the disturbance reached them, as is shown by the motion of a chip or cork on the surface, but the wave travels steadily outward. Wind, blowing over a field of grass or grain, causes waves, the heads vibrating to and fro. A wave, then, is *the transmission of a vibration.* The word was first used in connection with water, but the vibrations in water waves are somewhat complex, and we shall consider first a case of simpler vibrations. For this purpose we use a heavy spiral spring, *AB,* suspended from a ceiling (or a rubber tube

Fig. 157. Water Waves

attached to a wall). Waves can be started along it by moving the end *A* to and fro at right angles to its length (Fig. 158). As *A* is started in motion, it drags the next part with it, and this starts the next part after that, and so on. Each part takes up the motion in succession, and so the successive displacements of *A*, in one complete vibration, becomes spread out in the form of a wave.

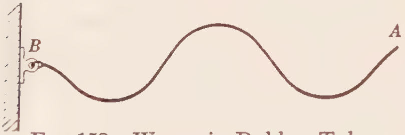

FIG. 158. Waves in Rubber Tube

While these are not water waves, it is convenient to use the terms *crest* and *trough* for the two halves of each complete wave, a crest being a bend toward one side, and a trough the bend toward the other side. The *length* of a wave is the distance from the middle of a crest to the middle of the next crest, or from the middle of a trough to the middle of the next trough. The wave-length is greater the slower the motion of the end *A*.

When the motion given to *A* is a simple vibration, the wave is called a *simple wave*. Its form is the same as that of the graph of the vibration of the point *A*, spread out along *AB*.

Describe the waves produced by a stone dropping in water. In what direction does the wave travel? In what direction do the water particles move? Define a wave. How may waves be made to travel along a rope? What is the crest of a wave? The trough of the wave? What is meant by the length of a wave? What is a simple wave?

171. Velocity of Waves.—Any point *A* on a cord, along which waves are traveling, evidently makes one complete vibration in the time required for one complete wave (crest and trough) to pass. If the beginning of a wave is just at *A* at a certain moment, after one complete vibration of *A* the beginning of that wave is one wave length distant from *A*. If *A* makes *n* complete vibrations in one second, the waves travel *n* wave lengths in a second. The number of vibrations that *A* makes in a second is called the *frequency* of the vibrations. The distance the wave travels in a second is the velocity of the wave. Hence: **wave velocity = wave length × frequency.**

What is meant by the frequency of a vibrating body? What relation exists between the wave length, the velocity, and the frequency?

172. Addition of Waves.—Two sets of waves can be produced on the surface of a pond by dropping pebbles in it at two points. The effect at any point reached by both sets of waves is the sum of two wave motions. The general term for such additions of waves is *interference* of waves.

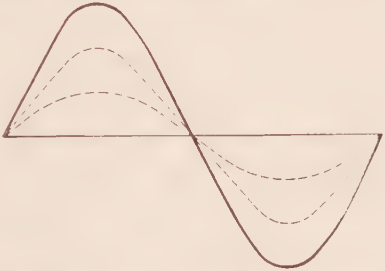

FIG. 159. Resultant of Two Waves in Phase and Having the Same Wave Length

Suppose two trains of simple waves to be traveling in the same direction on a cord. To find the resultant wave, we add the displacements due to the simple waves and draw a resultant curve. Thus in figure 159 we have two trains of waves, of the same wave length, represented by dotted lines. The resultant wave, represented by the heavy line, is evidently a simple wave of the same wave length as the separate waves. In this case the waves start together and are described as being in the same *phase*, and the resultant amplitude equals the sum of the separate amplitudes. In figure 160 the waves are not in the same phase, and the resultant amplitude is less than the sum of the separate amplitudes. Figure 161 shows

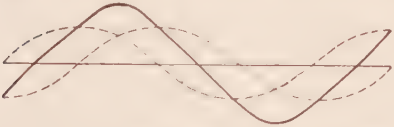

FIG. 160. Resultant of Two Waves Out of Phase

the result of adding two trains of waves with wave lengths as 2:1. The resultant wave is not a simple wave.

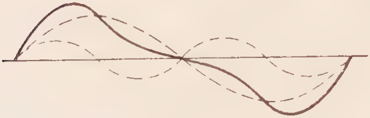

FIG. 161. Resultant of Two Waves, 2:1

A still more complex resultant is obtained when the wave lengths of the separate waves are not in a simple ratio. In figure 162 the component simple waves have wave lengths as 11:10. The resultant is a wave that swells out to a maximum, where a crest of one component falls on a crest of the other, and dies down to a minimum, where crest falls on trough.

What happens when two waves meet? What is meant by interference of waves? When are two waves in the same phase? What is the result of the interference of two such waves? What condition produces the maximum amplitude in the resultant wave? The minimum amplitude?

173. Two Kinds of Waves.—In the waves on a cord that we have been considering each part of the cord vibrates at right angles to the length of the cord. Such a wave is called a *transverse* wave. The parts of an elastic cord can also vibrate *along* the length of the cord. This is well shown by a large spiral spring (Fig. 163). If one end *A* of it is given a sudden push in the direction of the length of the spring, a momentary compression will be produced at *A*. This compression will at once start to travel toward *B*. On the other hand, if the end *A* is suddenly pulled, a momentary extension will take place at *A*, and this will also travel toward *B*. If we combine the two cases, that is, if we

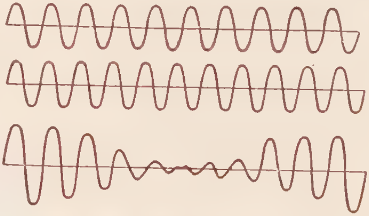

FIG. 162. Resultant of Two Waves, 11:10

give *A* a push and then a pull, a compression followed by an extension will travel along the cord. The push and pull at *A* is a vibration, a to-and-fro motion in the direction of the length of the cord. Such a vibration is called a longitudinal vibration, and the wave of compression and extension that travels along the cord is called a *longitudinal* wave.

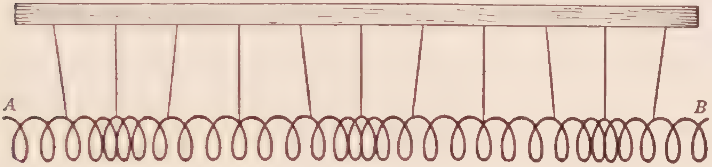

FIG. 163. A Longitudinal Wave

What is a transverse wave? Give an example. What is a longitudinal wave? Give an example.

174. Waves of Compression and Rarefaction.—Instead of the spring of § 173 consider a long tube *AB* containing air (Fig. 164). Suppose the end *A* of the tube to be closed by an elastic membrane *C*. If we push in suddenly on *C*, a compression will be started along the tube. If we pull out suddenly on *C*, a rarefaction will be started along the tube. If we cause *C* to vibrate inward and outward, that is, in the direction of the length of *AB*, compressions followed by rarefactions will traverse the tube. These are longitudinal waves in air. The particles of air vibrate in directions parallel to the length of the tube, that is, in the direction in which the wave travels. Each complete wave consists of a compression and the next rarefaction.

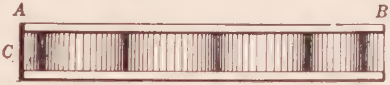

FIG. 164. A Wave of Compression and Rarefaction in Air

Waves of compression and rarefaction can be propagated in a gas, because it offers elastic resistance to being compressed or rarefied. It has no elasticity as regards bending, as a rod or a spring has, because a gas is a fluid. It is clear, therefore, that *waves of sound must be longitudinal waves,* that is, *waves of compression and rarefaction.*

How may compressions and rarefactions be produced in the air? Can they be produced in other gases? How do you know that sound waves are longtitudinal waves?

175. Curve for Waves of Sound.—Transverse waves on a cord are readily represented by drawing the actual shape of the cord (Figs. 159, 160). In longitudinal waves there is no such change of shape, and we cannot represent them so readily. We may draw a series of dots (Fig. 165) representing the closeness together of a line of air molecules in a train of waves. Or we may use a series of lines, spaced out to represent the compressions and rarefactions (Fig. 164). A simpler and clearer method is to draw a curve (Fig. 165) showing the amount of compression and rarefaction along the line in which the waves are traveling. At points on this line, erect perpendiculars to show the amount of compression or rarefaction at the point, that is, the amount the density of the gas is above or below the density when there are no waves. Lines drawn upward will represent compressions, and lines drawn downward rarefactions. A smooth curve through the ends of these lines will represent the whole train of waves. By this device we can represent longitudinal waves as readily as transverse waves.

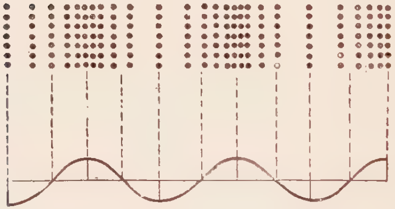

FIG. 165. Methods of Representing Longitudinal Waves

When the curve representing the sound wave is of the same form as the graph of a simple vibration (§ 169), we call the wave a *simple sound wave*. When two or more simple sound waves are added we get complex sound waves, the curves for which are obtained as in § 172.

How may curves be drawn to represent longitudinal waves? What do the crests represent? The troughs? Draw a simple sound wave.

EXERCISES

1. What is a vibration? What is meant by the amplitude of a vibration? What is meant by the period of a vibration?

2. What is a sympathetic vibration? What conditions are necessary for such vibrations to be produced? Give two simple examples.

3. What is the difference between a forced vibration and a sympathetic vibration?

4. Explain the operation of the children's string telephone. Would it work if the string were lying loosely on the ground?

5. Explain why some engines vibrate very much at one particular speed, and much less when the speed is greater or less.

6. What is a wave? With how many different kinds of waves are you familiar?

7. What do the terms longitudinal and transverse mean as applied to waves? In which kind of waves are there compressions and rarefactions?

8. What is the wave length at 20° C. of a tuning fork which vibrates 256 times per second?

9. In 1877 Koenig began to make a set of tuning forks ranging from 16 to 21,845 vibrations per second. At a temperature of 20° C. what are the wave lengths of these two extremes?

CHAPTER XVII

MUSICAL SOUNDS

176. Characteristics of Musical Sounds.—In distinguishing sounds from different sources, we take note of three familiar characteristics of sounds, namely, *loudness, pitch*, and *quality*. Any sound that has a definite pitch, such as the sound of a tuning fork, or a bell, or of the voice in singing, we shall call a *musical sound*. Other sounds, such as the hammering of a nail or the sawing of a board, are called *noises*. Loudness, pitch, and quality of sound refer to sensations in the ear, and depend on certain properties of sound waves.

Name three characteristics of sounds. Distinguish between a musical sound and a noise. Sounds may differ from each other in how many ways?

177. Loudness.—When we gently strike a tuning fork or bell, the sound produced is weak. A stronger blow produces a wider vibration of the fork or bell, and a louder sound results. Now it is evident that a larger amplitude of vibration of the sounding body must produce a larger amplitude of vibration in the air. Hence **the loudness of a sound depends on the amplitude of vibration in the sound waves**. The sound we hear becomes weaker as we move farther from the source, because the amplitude of the vibration becomes less, and less energy of vibration falls on the ear.

What determines the loudness of a sound? Why is the loudness of a sound affected by distance from the source?

178. Pitch.—The sound of a toy whistle is shrill, or of high pitch, that of an automobile horn is of medium pitch, while the tones of a church bell are deep or of low pitch. The cause of these differences can be shown by drawing a card along the teeth of a comb. When it is drawn slowly, a sound of low pitch is heard, but when it is drawn more rapidly, the pitch rises. Every time the card slips off one tooth and strikes the next, an impulse is given to the air, that is, a wave is started. The more numerous these impulses per second, that is, the more air waves started per second, the higher is the pitch.

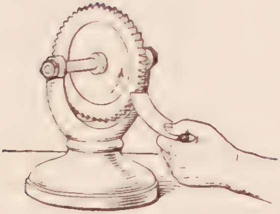

FIG. 166. Savart's Wheel

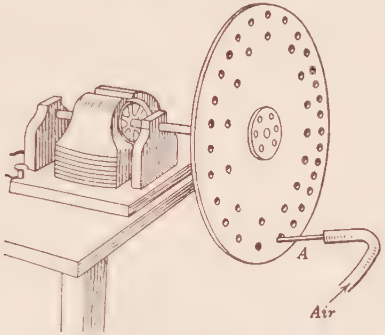

FIG. 167. A Disk Siren

When a machine saw cuts a board, the rise and fall of the pitch is due to the variation of the speed of the saw. *Savart's wheel* (Fig. 166) illustrates the same principle by the slipping of a card on a toothed wheel, rotating at high speed. From these experiments we see that **the pitch of a sound depends on the frequency of the vibrations of the source of the sound.** Relative motion of source and hearer also influences pitch. When a fire engine, with gong sounding, is approaching rapidly, we hear a sound of slightly higher pitch than when it is receding. This is called *Doppler's principle*.

What determines the pitch of a sound? How could you prove it? Describe a Savart's wheel. Why does the gong of a trolley car seem to rise in pitch as the car rapidly approaches?

179. The Siren.—A siren is an instrument for producing sounds by puffs of air that follow one another in rapid succession. The simplest form consists of a disk (Fig. 167) with circular rings of holes, and a tube through which air is driven under pressure. Each time a hole comes opposite the end of the tube, a puff of air through the hole takes place. If the disk is mounted on an electric motor, the number of rotations it makes per second is known. By multiplying this by the number of holes in a ring, we get the frequency of the puffs. With several rings of holes in the disk, we can get notes of different pitch. The ratio of the frequencies of the puffs for two rings is the ratio of the number of holes in the two rings.

What is a siren? How is it operated? Upon what does the pitch of the siren depend?

180. Musical Scales.—In music, a sound of definite pitch is called a *note*. In speech, we use notes of any pitch at random, but in music it is convenient to use only a certain series of notes, called a *musical scale*. The most familiar scale, called the *major scale*, consists of notes which are called by the letters, C, D, E, F, G, A, B, C′, D′, etc. This succession of sounds is heard when the white keys of a piano are struck in succession (Fig. 168), starting with the C near the middle of the piano, which is called *middle C*.

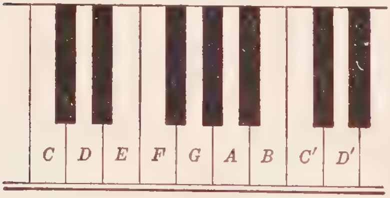

FIG. 168. Piano Keyboard

Between any two notes of different pitch there is, in the language of music, a certain *interval*, and special names are given to various intervals. Thus the interval from C to C′ is called an *octave*, that from C to G a *fifth* (G being the fifth note in the series of which C is the first), that from C to F a *fourth*, and so on. The name of a certain interval is, however, not confined to a certain pair of notes. The interval from D to D′, or from E to E′ is also an octave, while the intervals F to C′ and G to D′ are also fifths, and so on. Thus two notes may be of high pitch or of low pitch, and yet have the same interval between them.

These musical terms were in use before sound was studied scientifically. When the frequencies of notes were measured, it was found that two notes between which the interval is an octave always have frequencies as 2 : 1; when the interval is a fifth the frequencies are always as 3 : 2; and so on. Thus, what determines the interval between two notes is the *ratio of their frequencies*. Combinations of notes are used in music, and it is important to know what notes will go well together. Three notes sounded together are called a *triad*. There are three triads that are found to be especially harmonious, namely, C-E-G, F-A-C′, G-B-D′. These are called *major triads*. When the frequencies of these are measured, it is found that they are all as 4 : 5 : 6. It will be noted that all the letters in the scale occur in one or more of these triads. Hence the whole major scale may be considered as consisting of major triads. A *major chord* consists of a major triad together with the octave of the lowest note of the triad. The frequencies of the four notes are as 4:5:6:8.

The first line of the following table shows the frequencies of the notes in the major scale starting with C, according to the "international" pitch, the frequency of C being 261. In recent times there has been a tendency to raise the pitch of orchestral instruments, to obtain more brilliant effects. At one time C was as low as 256, and this pitch is still retained in making tuning forks for the study of Physics, because the number 256 is more convenient in calculations.

The second line contains the intervals between each note and C, for example the interval of an octave is 2, that of a fifth $3/2$, etc. The other lines indicate the major triads already referred to.

C	D	E	F	G	A	B	C′	D′
261	$293\frac{5}{8}$	$326\frac{1}{4}$	348	$391\frac{1}{2}$	435	$489\frac{3}{8}$	522	$587\frac{1}{4}$
1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	$\frac{2}{1}$	$\frac{9}{4}$
4		5		6				
			4		5		6	
				4		5		6

What is a musical scale? What is an interval in music? Define an octave. A fifth. A third. How great is the interval between F and C? Between C and E? How is the interval between two notes expressed mathematically? What is the ratio of frequencies between D and D′? Between C and G? What is a triad? A major triad? What are the ratios of the frequencies of the notes in the major triad? What is a major chord? What are the ratios of the frequencies of the notes? What is the frequency of middle C on the piano? What frequency is taken for middle C in Physics? Why are they not the same?

181. Other Musical Scales.—Any series of notes with the same succession of intervals as from *C* to *C′* in § 180 is called the *diatonic scale.* In the teaching of singing it is memorized by the sounds do, re, mi, etc. To get the same succession of intervals by starting with any other white key on the piano, certain intermediate notes must be used, and these are supplied by the black keys of the piano. From figure 168 it will be seen that this gives twelve steps between *C* and *C′*. This succession of intervals is called the *chromatic scale.* In tuning a piano, all intervals from one note to the next are made equal. The scale thus produced is called the *equal temperament scale.* Tuning in this way throws the diatonic scale on the piano very slightly out of tune, while a singer or violinist tends to follow a true diatonic scale, but the differences are too slight to cause appreciable discords.

What is the diatonic scale? The chromatic scale? Why are the black keys needed on the piano? What is the scale of equal temperament? Is the scale of a piano a scale of equal temperament? Does a violinist playing alone use the scale of equal temperament?

182. Quality.—Musical sounds may be of the same loudness and pitch and may nevertheless be readily distinguished as coming from different sources. Thus, when the note C is sounded by a violin string, a clarinet, and by the voice, the ear recognizes at once that the sounds are quite different, and they are described as differing in *quality* or *timbre.* The cause of these differences is revealed if the waves producing the sounds are traced by instruments devised for the purpose. The waves in the three cases mentioned are as shown in figure 169. The upper wave is that of a violin string, the next is that of a clarinet, and the lowest is that of the voice singing the syllable *ah.* From these illustrations we see that **the quality of a sound depends on the form of the waves that produce it.**

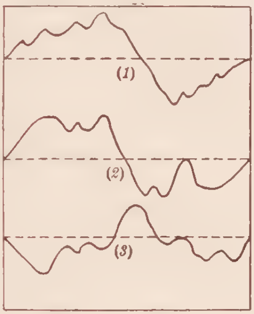

Fig. 169. Complex Sound Waves

Of the three wave forms in figure 169, the upper is evidently the simplest. Sounds having a simple wave form are what musicians call *pure tones.* Pure tones are readily obtained by drawing together the prongs of a tuning fork that is mounted on a sounding box (Fig. 170) and releasing them. Most sounds are complex, that is, they consist of various mixtures of pure tones. The waves that cause them are complex waves, produced by adding simple waves, as described in figure 161. These simple waves of higher frequency are produced by component sounds of higher pitch, called overtones. It is the number and relative intensity of these overtones which determine the quality of the sound as heard by the ear. A radio amplifier

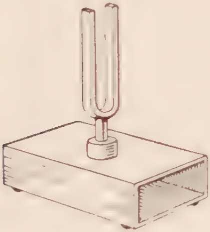

Fig. 170. Tuning Fork Mounted on Resonance Box

or loud speaker, by emphasizing some of these overtones and suppressing others, distorts the sound and gives an undesirable quality to it. Horn speakers usually respond more readily to the higher overtones while cone speakers amplify the lower ones to a greater degree. Thus neither gives a perfect reproduction of the original music.

If two musical sounds are of the same pitch and the same loudness, are they necessarily alike? Why not? Upon what does the quality of a sound depend? What are pure tones? Are tones of the voice pure tones?

183. Beats Between Sounds.—When a white key and an adjacent black key near the bottom of the keyboard of a piano are struck at the same time, a throbbing of the sound is heard. The throbs are slow and can almost be counted. When the same is done higher up on the keyboard, the throbs are more rapid. These throbs, produced by two notes of nearly the same pitch, are called *beats*.

Two tuning forks, of the same pitch and mounted on sounding boxes, can be thrown out of unison by attaching a small piece of wax to a prong of one. If they are then sounded together, beats slow enough to be counted are heard. When a larger piece of wax is used, the beats are more frequent. **The number of beats in a second is equal to the difference of the frequencies of the two forks.**

Beats result from the addition of two trains of waves of different wave lengths (§ 172). The sound swells out and dies down, because sometimes the waves agree and their effects are added, and sometimes they are opposed, so that they neutralize each other and produce a momentary silence. The discordant effect produced by sounding two very near notes at the same time is due to the beats which the ear hears. Helmholtz showed that in all cases musical discords are due to beats, either between two fundamental tones or between higher tones that accompany the fundamentals.

What is meant by beats? How are they produced? What determines the number of beats between two sounds? Why do two piano strings of slightly different pitch produce beats when sounded together?

EXERCISES

1. In how many ways do musical sounds differ from each other?

2. What occurs to a tuning fork as the sound dies away?

3. Upon what does pitch depend? Describe a simple experiment to prove this.

4. What do you mean by "timbre" or "quality"?

5. In what lies the difference: C on a violin and C on a piano?

6. Why do you not hear the vibrations of a second's pendulum as a note?

7. Why does the pitch of the sound of a buzz-saw drop when the saw strikes a knot?

8. What is the diatonic scale? How does it differ from the chromatic scale?

9. In what way does music played on the piano differ from music played on an organ?

10. Show how the diatonic scale is developed from three major chords.

11. Why is the sound from a radio loud-speaker more or less unnatural?

12. Describe two ways in which it would be possible to determine the frequency of a given tuning fork.

13. It is very difficult to detect a difference of pitch caused by the difference of frequency of one vibration per second, and yet the three strings of each of the upper notes of a piano are tuned much more closely than this. How is it done?

PROBLEMS

1. Compute the vibration rates of the diatonic scale, starting with middle C as 256.

2. The highest tone which the ear can recognize is about 30,000 vibrations per second. What is the wave length of this note?

3. Examine a piano and calculate the frequency and wave length of the highest note produced by it and also the lowest, assuming the frequency of middle C to be 256.

CHAPTER XVIII

MUSICAL INSTRUMENTS

184. Sources of Musical Sound.—It is convenient to classify musical instruments as *stringed* instruments, *wind* instruments, and *percussion* instruments, as the terms are used in an orchestra. These terms refer to the nature of the vibrating body to which the sound is due, namely, vibrating strings or cords, air columns, and rods or membranes. Only one or two from each class will be considered here.

Name three classes of musical instruments. Mention an example of each.

185. Vibrating Cords.—When a cord, stretched between two supports, vibrates, it moves to and fro between two extreme positions (Fig. 171). A monochord for the study of such vibrations consists of a wire AB stretched on a board or box (Fig. 172), with a weight at one end, by means of which the tension of the cord can be changed. A movable bridge C can be placed at various positions under the wire, so that different lengths of wire can be used, and the length in use at any time can be read on a scale beneath the wire. Four tuning forks that give a major chord, for example, C. E. G. C′, are useful for finding the pitch of the note given by the wire. Careful study shows that the pitch of the note given by the wire depends on the length of the wire, the mass of a unit of length, and its tension. The mass of a unit of

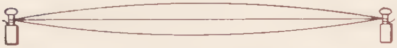
Fig. 171. A Vibrating String

length depends on the material of which the string is made, and its diameter.

(1) **The vibration-frequency varies inversely as the length of the vibrating wire.** For example, if the tension of the wire is adjusted so that the whole wire gives the note C, *half* of the wire will give C′, the vibration frequency of which is *twice* that of C, and *two-thirds* of the wire will give G, the vibration frequency of which is *3/2* that of C, and so on. The violinist makes use of this relation to get higher notes on a violin string by sliding his finger up the string.

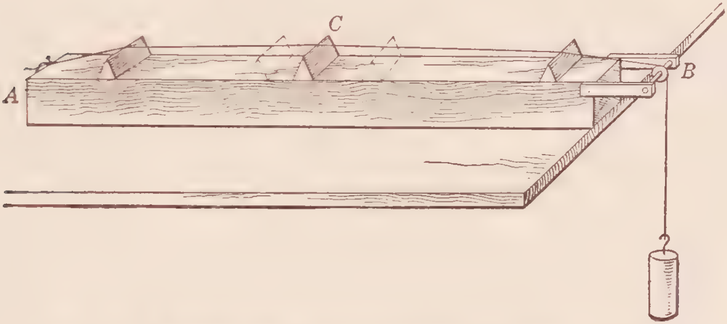

FIG. 172. A Monochord for Studying the Vibration of Strings

(2) **The vibration frequency is proportional to the square root of the tension.** When the tension is such that the pitch of the whole string is C, it will take four times as great a tension to produce C′. In tuning a violin the tension is adjusted until the note is right, and the piano-tuner tunes the wires of a piano in the same way.

(3) **The vibration frequency varies inversely as the square root of the mass per unit length of the wire.** The lower notes of the piano are produced by heavy wires, while lighter wires are used for the higher notes. The same is true of the strings of a violin.

Describe a monochord. How can one find the pitch of a note on the monochord? Upon what three things does the pitch of a vibrating string depend? State the laws governing the pitch of a string. What must be done to the tension of a string to make its pitch an octave higher? Why are the lower strings on a piano of heavy wire? Why are the lower notes struck on longer strings?

186. Partial Vibrations of a Cord.—A cord can be made to vibrate as two halves, by putting the movable bridge under the middle of the wire and plucking or bowing either half (Fig. 173). By putting the bridge under a point one-third, one-fourth, and so on, from one end, and sounding the shorter part, we get a series of higher tones. Remembering how the frequency depends on the length, we see that if the frequency of the whole cord is N, the frequencies of these higher tones are $2\,N$, $3\,N$, $4\,N$, $5\,N$, etc. Such a series of notes are called *harmonics* of the note of frequency N, which is called the *fundamental* of the series.

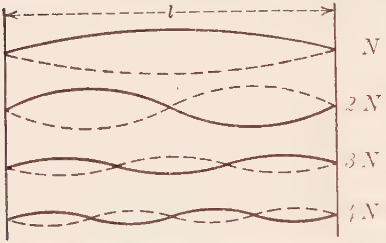

Fig. 173. Partial Vibrations of a Cord

The notes, higher than its fundamental, that a vibrating body can give, are called *overtones* of the body. In the case of the vibrating cord the overtones are harmonics of the fundamental. We shall see that this is not true of all sounding bodies.

The parts into which a vibrating cord divides are called *loops* or vibrating segments. The points of division do not vibrate and are called *nodes*. While the cord oscillates to and fro between two extreme forms, its form at any moment is that of a train of waves, and the whole set of loops is spoken of as *stationary waves*. They are, in reality, the result of two trains of waves traveling in opposite directions and reflected at the ends. Stationary waves are readily formed by sending waves along a cord that is fixed at one end, as in figure 158.

How may a wire be made to vibrate in sections? Will the notes so produced be of higher or lower pitch than that made by the entire string? Why? What is the fundamental note of a string? What are harmonics? How are they produced? Define overtones. Are harmonics overtones? Are all overtones harmonics? Explain. What are nodes and loops in a vibrating string? What are stationary waves in a string? How may they be produced?

187. Complex Vibrations of a Cord.—The partial vibrations, produced separately by sounding a part of a cord, can also take place at the same time as the fundamental. If a string be bowed at one-fourth from one end, and the finger be then touched very lightly at the middle, the fundamental tone will cease, and the note due to the cord vibrating as two halves will be heard. Since touching with the finger could not have produced an additional tone, this partial vibration must have been present from the start. In the same way, by sounding the cord and touching it at one-third, one-fourth, etc., from an end, we can show the presence of higher harmonics.

But the combination of fundamental and overtones, produced by bowing the cord, does not include all possible overtones. The first overtone is absent when the string is bowed exactly in the center. The second overtone is absent when the bowing is exactly at one-third from one end, and so on. Thus, by bowing at different points, we get different combinations of the fundamental and overtones. Each such combination produces a sound of separate quality. The best quality of tone is produced by sounding a string at about one-eighth from one end. This is therefore the position usually chosen for striking a piano wire by the hammer. It is also the average distance at which the violinist bows a violin string, but he varies the distance somewhat to produce tones of different qualities.

Does a vibrating string produce overtones at the same time as the fundamental? How can this be shown? Are the same overtones always present in the sound produced by a vibrating string? Upon what does the quality of the note depend? How can the violinist vary the quality of the tones of his violin?

188. Vibrations of Air Columns.—The cap of a fountain pen is open at one end. By blowing across the open end a musical sound can be produced. Harder blowing produces a higher note. The air in the tube is set into vibrations by the blast of air across the end, and it communicates its vibrations to the outside air, thus producing air waves, which reach the ear. Notes can also be produced by blowing across an end of a tube open at both ends, such as a piece of glass tubing. The pitch of the note depends on the length of the tube. A short tube gives a higher note than a longer one, just as a short vibrating wire gives a higher note than one of greater length (§ 185).

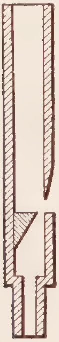

Fig. 174. Organ Pipe in Cross Section

Organ pipes are tubes open at one or both ends. When only one end is open, the pipe is called a *stopped pipe;* when both ends are open, it is an *open pipe.* The vibrations are started by blowing through the mouthpiece (Fig. 174). This is an opening through which a blast of air is driven from a wind chest to which the pipe is connected.

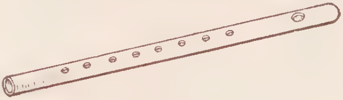

Fig. 175. Flute

Toy whistles and flutes (Fig. 175) are open pipes. The whistle has a mouthpiece like that of the organ pipe, but in the flute there is merely an opening across which air is blown to start the sound. On the side of the tube there is a series of holes which can be closed by the fingers or by stops. By means of these, notes of different pitch can be obtained, for the effective length of the air column is the distance from the mouthpiece to the nearest uncovered opening (Fig. 176).

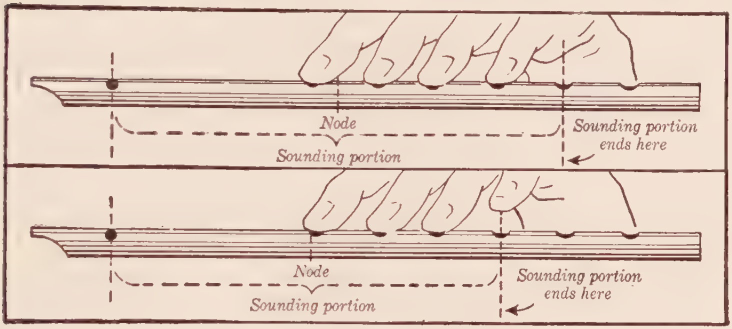

Fig. 176. The "Tin Whistle."
This figure illustrates the way in which the different notes of the scale are obtained.*

Why does blowing across the mouth of a small bottle give a musical note? Will a longer bottle give a higher or lower note? Describe an organ pipe. Name two kinds of organ pipes. Upon what does the pitch of the pipe depend? How is a flute made to sound? How is its pitch varied?

189. Resonating Pipes.—A glass tube with both ends open becomes a stopped pipe if one end is held beneath water in a tall jar. The length of the air column in it can be changed by raising it or lowering it (Fig. 177). When a tuning fork with a frequency of 512 is struck and held above the tube, no particular effect is noticed, until the length of the air column is about 6 inches. Then a loud sound is emitted by the tube.

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At this length the tube *resonates* to the fork, that is, it takes up the energy of vibration from the fork and gives it out again as air vibrations.

When a tuning fork, held above the tube, is moving downward, it sends a compression down the tube. This is reflected at the water, and comes back to the open end. When the prong of the fork is moving upward, it starts a rarefaction, which travels down the tube and is reflected, and comes back just as the prong is starting downward again. This process, repeated many times, produces wide vibrations of the air in the tube, so that it emits a loud sound. It is evident that the air wave traverses the length of the tube four times while the fork is making one complete vibration. The distance the sound travels in one complete vibration is the wave length of the sound (§ 170). Hence **the wave length of the stopped pipe is equal to four times the length of the tube.***

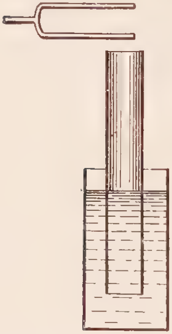

FIG. 177. Determining Air Length by Resonating Air Column

How may the air in a tube be made to reinforce a tuning fork? What adjustment has to be made? Why? How long does the tube have to be in comparison to the wave length of the sound?

190. Resonators.—The coöperation between the fork and the resonating tube, just described, is an example of resonance or sympathetic vibrations (§ 168) in sound, and such a tube is called a resonator. The "sounding boxes" frequently attached to tuning forks are also resonators. The sound of the tuning fork alone is a weak sound that lasts for a long time; when the resonance box is attached, a loud sound is emitted, but it lasts for a much shorter time.

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* Strictly speaking, the length needs to be corrected by adding about one-half of the radius to the length.

Two tuning forks of the same pitch, on resonance boxes, will resonate to one another. When they are placed on a table and one is sounded, the other will take up the vibrations and will be heard when the first is stopped (sympathetic vibrations).

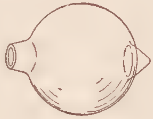


FIG. 178. Helmholz Resonator

Other forms of resonators are used. Spherical resonators (Fig. 178) have been employed for analyzing mixed sounds. Each will select from a mixture of tones the one of the same pitch as its own, if that is present. In this way, even the complex sounds of the voice have been analyzed into pure tones. A note sung loudly into a piano, with the loud pedal held down, will be taken up by the wires of the same pitch as the tones of the voice.

An organ pipe is in reality a resonator. The sound produced at the mouthpiece of the pipe by the air blowing against the sharp lip is a complex sound, like the sound you can produce by blowing against the edge of a knife. From this the pipe selects the tone that it can itself emit, and resonates loudly to it.

What is a resonator? What effect has a resonator on the sound of a tuning fork? What is meant by sympathetic vibration? How can resonators be used to analyze complex sounds? How is resonance illustrated in the organ pipe?

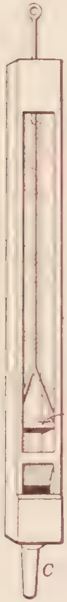


FIG. 179. The Pitch of an Organ Pipe Depends on Its Length

191. Pitch of an Organ Pipe.—To find how the pitch of an organ pipe varies with its length, we may use a stopped pipe that can be adjusted in effective length by a movable plug (Fig. 179). As a means of comparing the frequencies of the notes, we may use a monochord, since we have already learned the law of its variation of pitch with length. If we tune the monochord until it gives a note of the same pitch as the full length of the pipe, it will be found that half the length of the cord gives the same note as half of the pipe's whole length, two-thirds of each again give the same note, and so on. Hence the law of variation is the same in both cases. Since the frequency of the cord varies inversely as its length, **the frequency of an organ pipe varies inversely as its length.** This law can also be verified if four pipes marked C, E, G, C′, are available. The frequencies of these notes are as 4:5:6:8 or in the ratios 1:5/4:3/2:2, and it will be found that the lengths of the pipes are as 1:4/5:2/3:1/2.

A short open organ pipe can usually be made to sound as a stopped pipe, by placing the hand over the open end. It will thus be found that **a pipe of given length is an octave higher when open than when stopped,** or, for the same pitch, an open pipe must be twice as long as a stopped pipe.

Upon what does the pitch of an organ pipe depend? State the law which governs the frequency of an organ pipe. How does the pitch of an open pipe compare with that of a closed pipe of the same length?

192. Qualities of Tone of Open and Stopped Pipes.—From the preceding it might seem that open pipes alone, or stopped pipes alone, would suffice in an organ. But an open pipe and a stopped pipe of the same pitch give notes that differ in quality. The reason for the difference is found in the overtones which each produces along with the fundamental. If the frequency of the fundamental note from each is N, the overtones produced by the open pipe are $2N$, $3N$, $4N$, $5N$, *etc.*, while those produced by the stopped pipe are $3N$, $5N$, $7N$, *etc.* It will be noticed that $2N$, the octave of the fundamental, is never present in the note of the stopped pipe. This accounts for the duller quality of tone of a stopped pipe and its greater suitability for solemn effects.

Why are both open and closed pipes used in an organ? What overtones are given by a closed pipe? By an open pipe? Which pipe gives the more brilliant tone?

193. Percussion Instruments.—A rod clamped at one end, for example, a hat-pin in a vise, can vibrate in a number of ways (Fig. 180), and, if the vibrations are sufficiently rapid, they produce a fundamental and various overtones. A tuning fork is essentially a pair of rods, clamped to the stem. Its overtones are high and weak (except when it is struck violently) and produce little effect on the ear. Vibrating reeds, or strips of metal, are the sources of sound in the mouth organ and the harmonicon. In the clarinet, oboe, or bassoon there is a reed at the end of a pipe. The pitch of the note is determined by the length of the pipe, but the reed has a marked effect on the quality of the tone. In the jews-harp a vibrating reed produces a fundamental and various overtones, from which the cavity of the mouth, acting as a resonator, selects the one desired.

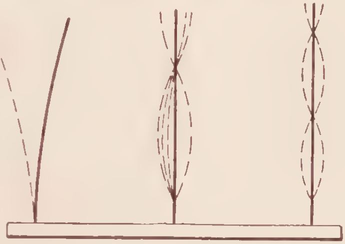


FIG. 180. Vibrating Rods

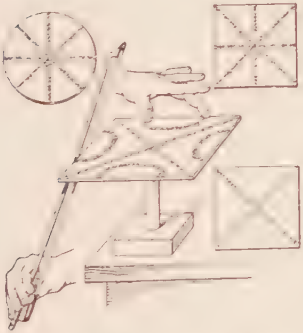


FIG. 181. Sounding Plates

A square or round plate of metal, the middle of which is screwed to the end of a rod, can be made to vibrate in a great number of forms (Fig. 181) by stroking it with a bow. These forms are clearly shown by sand, sprinkled on the plate. The sand leaves the parts that vibrate, and gathers on the nodes or lines of no motion.

A bell may be considered as a round plate that has been moulded into the form of a cup, and its vibrations are somewhat like that of the plate. It produces a fundamental and a series of overtones, one of which is usually louder than the fundamental.

Vibrating membranes are used in drums. The vibrations are at right angles to the surface, and their frequency depends on the tension of the membrane, which is adjusted, in tuning the drum, by screws. The ear-drum is a membrane that performs forced vibrations, when sound waves act on it.

Percussion instruments produce sounds by the striking of a rod, bell, plate, or membrane. Each, when struck, gives rise to a fundamental and overtones, but the overtones are not usually harmonics of the fundamental.

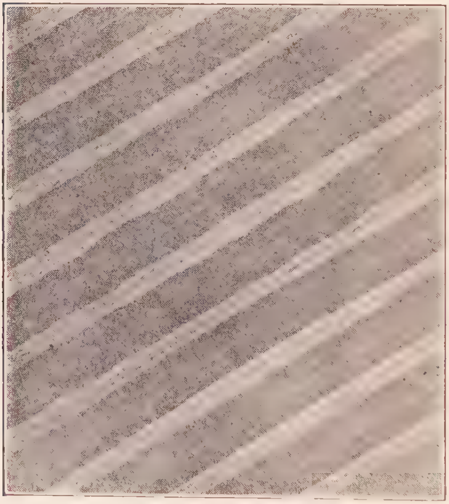


FIG. 182. Phonograph Record

What other objects besides strings and air columns can be made to vibrate? How may the vibrations of a plate be studied? Mention several musical instruments and explain the source of the sound in each case. Why is the "drum" of the ear so called?

194. The Phonograph.—In the phonograph, invented by Edison, a thin metal disk is caused to vibrate by sound waves, and the vibrations are recorded on a disk of hard wax, by means of a short needle, attached to the metal plate. The vibrations of the metal disk are forced vibrations, the frequency of which is that of the sound waves that cause them. The needle plows a fine furrow in the wax, the depth varying with the amplitude of vibration of the metal disk. The furrow is therefore a record of the vibrations of the disk, however complex they may be. The sound can be reproduced by allowing the needle to travel again along the furrow and so set the metal disk into vibrations, which reproduce the original sounds. In the gramophone, the needle moves sidewise on the wax disk, producing a wavy line of varying width, instead of a furrow of varying depth. A phonograph makes a curious sound when it is running down, because the frequency of every note is decreasing, and its pitch is therefore falling. (Fig. 182.)

How is the record of a sound preserved in the phonograph? How is it reproduced? How can the pitch of a piece played on a phonograph be altered?

EXERCISES

1. Why are the strings of a violin of different thicknesses?

2. Why are the bass strings of a piano wrapped with wire?

3. Why are three strings used for each of the higher notes of a piano?

4. Why cannot the piano be constructed to play the diatonic scale?

5. What is the function of the bridge of a violin?

6. Explain the action of the sounding board of a piano. Why are different parts of the board of different thicknesses?

7. If you place your foot on the loud pedal of a piano and then sing a note the piano will respond. Explain.

8. In certain churches certain notes seem to shake the whole building, while louder notes of higher or lower pitch have no such noticeable effect. Explain.

9. Mention some musical instruments that employ forced vibrations.

10. Explain just how the sound is produced when one blows across a hollow key.

11. In what type of instruments are sympathetic vibrations used?

12. Give, with the aid of a diagram, your reason for believing that the length of a resonance column, stopped at one end, is $\frac{1}{4}$ the wave length of the note.

13. Will the pitch of an organ pipe be the same in winter as in summer?

14. How do you account for the fact that open organ pipes give richer sounds than stopped ones?

15. How do you account for the many tones to be obtained from a bugle?

16. Draw a diagram showing your idea of the spiral line on a Victrola phonograph disk.

17. The outer edge of a phonograph disk moves faster under the needle than the inner ring. How is correct pitch maintained?

18. It is desired to play an accompaniment on a piano to a song sung by a phonograph. How can the instruments be brought into tune?

19. Draw a diagram showing the appearance of a loud note as it would show on a phonograph record and the same note played softly.

20. Why do soft materials absorb sound?

21. Can you suggest a remedy for a hall in which it is difficult to understand a speaker?

PROBLEMS

1. At a temperature of 18° C the resonating column that responds to a certain fork is 6.5 inches long. What is the frequency of the fork?

2. What is the length of a resonator which will respond to a C fork the frequency of which is 512, the temperature being 20° C.?

3. A certain police whistle has a tube $3\frac{1}{2}$ inches long. What is its frequency at 20° C.?

4. What effect would it have on the pitch of the whistle in the last question if it were used in zero weather?

5. An open organ pipe is 3 ft. long. What is the wave length of the note that it produces? What is the wave length of a stopped pipe of the same length?

CHAPTER XIX

THE USEFULNESS OF SOUND

195. The Advantage of Two Ears.—By the use of both ears we can find the direction from which a sound comes more accurately than we could with only one ear. If the ears are equally acute, the sound is louder at the nearer ear, and, by turning the head, we can find the direction of a continued or repeated sound with considerable accuracy.

Of what advantage is it to us that we have two ears instead of one?

196. Use of Sound in Navigation.—As an aid to navigation in foggy weather, many vessels are provided with two instruments, somewhat like telephone transmitters, on the opposite sides of the vessel, and beneath the surface of the water. These are for the purpose of detecting the sound of a submerged signal bell near the shore, the sound being conveyed through the water. The sounds received by the instruments are transmitted to the navigating officer on deck by electric circuits, as in the ordinary telephone service on land (or sometimes by tubes). By listening to the two sounds through telephone receivers at the two ears, and then altering the direction of the vessel until the sounds are of equal intensity, the direction of the vessel from the signal bell can be found. There are, however, special devices which make it possible to find the direction of the bell without altering the direction of the vessel.

The depth of the water beneath a vessel is sometimes found by the reflection of sound from the ground beneath the water.

Where the water is very deep, the method is like finding the distance of a reflecting surface on land by noting the time required for an echo of the voice to come from the reflecting surface. The sound is made beneath the water, and its echo from the bottom is heard by a receiver placed beneath the water. It is, of course, necessary to know the velocity of sound in water. A different method is used when the water is not very deep, for example not much deeper than the length of the vessel. In this case a receiving apparatus near the bow of the vessel is used to find the direction of the sound of the propeller as heard by reflection from the bottom. From the direction and the length of the vessel, the depth of the water can be calculated. You can easily draw a diagram to show how the calculation could be made.

How are under water sounds utilized in navigation?

197. Use of Sound in Warfare.—"Sound-ranging," or finding the position of a large gun by its sound, was of great importance in the World War. For this purpose very delicate recording instruments for giving the exact moment of arrival of the sound were used. The position of the gun could be calculated from the records at three stations, together with the known velocity of sound, allowance being made for temperature and the direction of the wind. In this way, the position of a gun at a distance of six miles could be found with an accuracy of about 50 yards. (Fig. 183.)

The direction of a submarine was found from the sound of the propeller by methods similar to those described in § 196. In this way, the direction of a submarine several miles distant could be found with an error of only two or three degrees, and, on closer approach, the direction could be found more accurately.

How may the location of a gun be learned from the sound it makes? How may a submarine be located while it is still invisible?

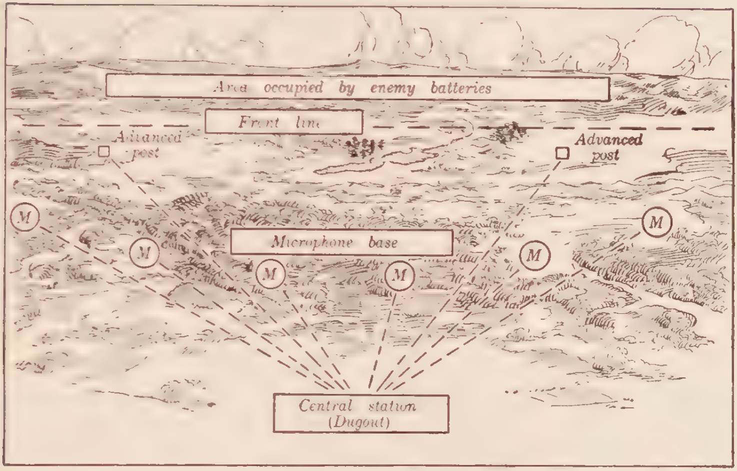


FIG. 183*a*. Arrangement of a Sound-Ranging Station *

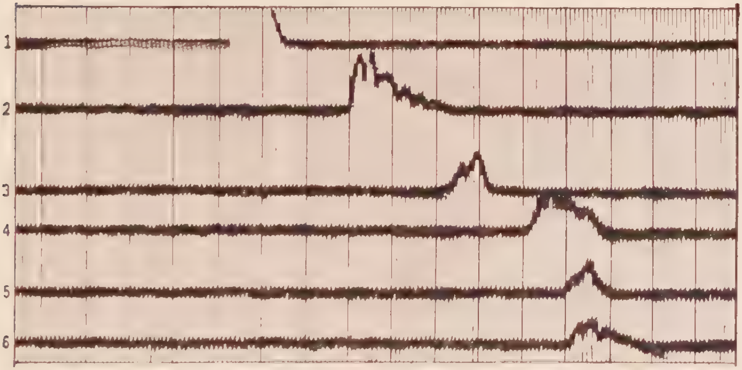


FIG. 183*b*. A Piece of Kinematograph Film, Showing the Effect of a 15 cm. Howitzer

The horizontal lines are the records made by the recorders, and are unbroken straight lines until the gun wave arrives. The vertical lines show the time, there being 100 to the second.*

* By permission from *The World of Sound* by Sir William Bragg. Published by E. P. Dutton & Company.

198. Why It Is Hard to Hear Clearly in Some Halls.—Hearing is often difficult in a nearly empty, unfurnished hall. A sound persists in it for several seconds, in the form of a continuous echo. Since a speaker usually utters two or three syllables per second, the sounds overlap and produce confusion. The continued echo in such a hall is called *reverberation.* If the walls did not reflect any sound, there would be no such effect, and it can be greatly reduced by covering some part of the walls with soft materials that absorb the sound. It is usually not a matter of importance on what wall or part of a wall the covering is placed. This is because the distance that sound travels in a second, about 1130 feet, is very large compared with the width, length, or height of an ordinary hall. The sound starts out in all directions from the speaker and is reflected many times in a second, so that the amount of sound that falls on a square foot of wall-surface is everywhere about the same. Yet there are places in some halls where somewhat more or less than the average amount of sound falls, and, for the very best effects, the proper position for placing the deadening material must be very carefully studied.

The reader may have heard of cases in which the attempt has been made to improve the hearing qualities of a hall by stretching fine wires across it. These have no more effect than a fishing line has on the flow of a river.

Why is it more difficult to hear in an empty hall than in one filled with people? What are reverberations? How may the reverberations in a hall be lessened? What effect has the stringing of wires across the hall?

199. The Greatest Service of Sound.—Sound is one of the most useful forms of energy. Speech is produced by the vibrations of a pair of membranes in the throat called the *vocal cords*, which are set into vibration by air forced through them by the lungs, and the sound is heard by means of the vibrations of a membrane in the ear called the *ear-drum*. Between the speaker and the hearer sound consists of vibrations of the air, and without these vibrations vocal organs and ears would be useless. Civilization came by men forming groups and taking counsel together for mutual aid, and the most valuable means of communication was by sound waves. Think how different the world would be without sound waves! It would be a deaf-and-dumb world. Man would now be as uncivilized as he was many thousands of years ago. He would know nothing of music, for even the birds could not sing. Literature would probably not exist, for it began in the form of recited poems and tales. You can think of many other things that would be lacking. For a large part of what we call civilization, we are indebted to the invisible vibrations of air that constitute sound.

EXERCISES

1. Why does a man who is deaf in one ear sometimes find it difficult to determine the direction of a sound?

2. If a boy is blindfolded and you snap your thumb and finger above his head, he sometimes thinks that the sound comes from behind or from in front. Explain.

3. Can you think of a reason why the depth of the deepest ocean cannot be found by one of the methods described in this chapter?

4. If you listen to a speaker in a large tent, you may sometimes hear his words quite distinctly, though the sound may seem faint. Explain.

5. Why do your footsteps seem to make so much noise in an unfurnished house?

6. Why is it often more difficult to speak to a small audience than to a large one in the same auditorium?

CHAPTER XX

HEAT

200. Sources of Heat.—Water fresh from the well or from the city water mains feels cold; but when it has stood over the fire for a while it feels hot. It evidently must have received something from the fire. A cold stone placed in the sun in summer also becomes warm or even hot. It must have received something from the sun. Place a penny on the table and on top of it place another penny that has been heated by being held in the flame of a match. After a few seconds the two will feel equally warm. In all such cases something passes into the cold body and makes it hot. That something we call *heat*. We shall define it more precisely later.

When you step from the shade into the broad sunshine, you at once become aware that the *sun* is one of the important sources of heat. Distant as it is, it sends us vastly more heat than we receive from any other source. Without it life on this earth would be impossible; for plants would not grow, and the earth would everywhere be colder than it is now at the North Pole.

Next in importance as a source of heat is the fuel supplied us by forests and coal mines. But wood and coal do not yield heat until they combine with the oxygen of the air. This supply of heat is therefore due to *chemical action*.

That the earth contains large quantities of heat is shown by the hot water thrown out by geysers, and by the lava or molten rock that flows from active volcanoes. This *internal heat of the earth* is not of much practical value, but it is of interest as an indication of the past history of the planet on which we live.

Many forms of *mechanical action* give rise to considerable quantities of heat. We rub the hands together to warm them when they are cold. Matches are ignited by rubbing on a rough surface. The American Indians lit their fires by the friction of one piece of wood on another (Fig. 184*a*). When there is much friction between an axle of a railway car and the bearing a "hot box" results. A blacksmith can heat a piece of iron by hammering it, and the head of a nail is heated when the nail is driven into wood. Air or any gas is heated by sudden compression, as is shown by the heating of a pump used to inflate the tire of a bicycle. In Tyndall's Fire Syringe (Fig. 184*b*) a small quantity of tinder in the cylinder is ignited by suddenly pushing a piston into the cylinder (the principle of the Diesel engine).

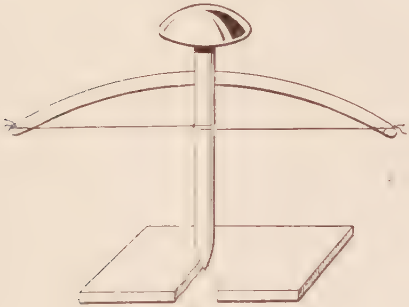


FIG. 184*a*. Making Fire by Friction

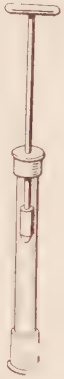


FIG. 184*b*. Tyndall's Fire Syringe

Mention four important sources of heat. Which is the most important? Give an illustration of each.

201. The Nature of Heat.—Heat was long thought to be a form of matter and was called *caloric*. It was supposed that, when water was heated over a fire, caloric passed from the fire into the water, and had the property of making the water hot, just as sugar has the property of making water sweet. But sugar also makes the water heavier, whereas no change in the weight of a body takes place when it is heated. Benjamin Thompson, Count Rumford, an American whose life was spent mostly in Europe, observed while superintending the boring of cannon in Munich, that very great quantities of heat were produced, without any change of weight. To do the work of boring, energy had to be expended, and heat was obtained. He was thus led to the conclusion that heat is itself a form of energy, not a form of matter.

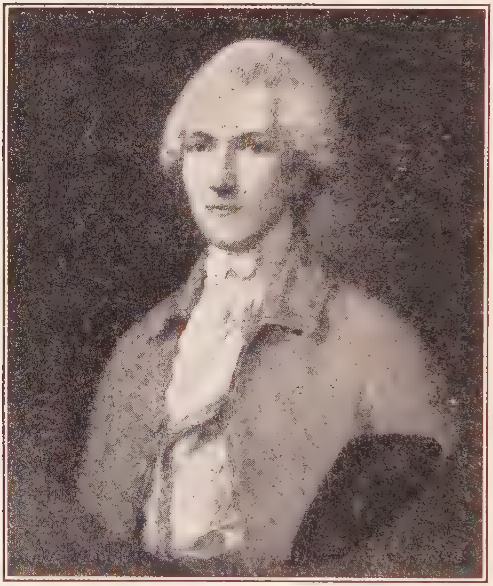


FIG. 184*c*. Benjamin Thompson, Count Rumford (1753-1814), born in Woburn, Mass., came very near to discovering the Conservation of Energy.

Somewhat later James Prescott Joule measured the heat produced by friction, the work being done by a weight that descended and therefore lost potential energy. His results showed a constant *rate of exchange* between the two—so much energy would, as it were, purchase just so much heat.

From such experiments it was concluded that *heat is a form of energy.* But what form of energy? To answer this, let us think of what takes place in the head of a nail when it is struck by a hammer. We know that the molecules in the nail are in continual motion, dashing to and fro and colliding with one another. The blow on the nail increases this motion of the molecules. The top layer of molecules receive the first impulse from the hammer, and vibrate with greater violence. Part of their increased energy of motion they hand on by impacts to the next layer, which in turn transfers some to the next, and so on. Thus the effect of the blow is to produce a general increase in the motion of the molecules, and this *energy of molecular motion is heat.*

What was the ancient belief regarding the nature of heat? How do you know that it is not the correct explanation? What led Count Rumford to the correct explanation? What further contribution did Joule make to the problem? What is the modern belief regarding the nature of heat?

202. The Conservation of Energy.—The kinetic energy which a hammer loses when it strikes an anvil is not lost, for it reappears in the form of heat, that is, kinetic energy of the molecules of the hammer and anvil. There is neither gain nor loss of energy in the process, merely a change from one form of energy to another. A steam engine transforms the heat of steam in a boiler into the kinetic energy of the motion of the flywheel. Again there is a transformation of energy but no change in its total amount.

In other parts of Physics we meet with other forms of energy, and we find that the same principle holds in all cases. We can change energy from one form to another and thereby do useful work, but *we can neither create nor destroy energy.* This is the great principle called *the law of the conservation* *of energy.* It helps us to understand many processes that would otherwise be puzzling, and wherever possible we should try to account for the changes of energy that take place.

State the law of conservation of energy. Mention several examples of the transformation of energy from one form to another.

203. Effects of Heat.—By the effects of heat we mean the changes in the properties of a body when it is heated or cooled. These are very numerous, but there are three principal changes of which many observed effects are different combinations, namely:

Changes of temperature
Changes of size
Changes of state.

Another effect will be considered when we come to the study of electricity. Heat also produces important chemical effects.

What is meant by the effects of heat? Mention three important effects of heat.

EXERCISES

1. Mention the important sources of heat and give illustrations of each.

2. What was the early belief as to the nature of heat? What do we know it to be?

3. State your idea of the changes in the molecular condition of a body when it is heated.

4. What is meant by the conservation of energy?

5. What becomes of the energy of a moving bullet? Of a wound-up watchspring?

6. What is the original source of the energy that runs our trolley cars?

7. A man carries bricks up a ladder. What was the original source of the potential energy they gain?

8. What was the original source of the energy of a rotating water-wheel? Trace its transformations.

9. What are the principal effects of heat? Give illustrations.

CHAPTER XXI

TEMPERATURE

204. Warmth and Coldness.—Everyone is familiar with a large number of terms used to describe how warm or how cold a body is, such as cold, cool, warm, hot. These terms refer to what we feel when we touch bodies. But our sensations are apt to be misleading in such matters. A room that appears comfortable to a person in good health seems cold to one suffering from a chill, and hot to a fever patient. When you first step into water for a swim, you are apt to shiver, but, after you have been in a few minutes, you may find the water quite comfortable.

Place the right hand in a vessel of hot water and the left in one of cold water and keep them so for a minute. Then plunge both into a vessel of lukewarm water. It will seem cold to the right hand and hot to the left. Hence we cannot place absolute reliance on the evidence of feeling or sensation.

Is your own feeling a safe guide in determining whether a thing is really warm or cold? Give illustrations of unreliability.

205. Temperature.—As we cannot convey accurate ideas by the vague words warmth and coldness, for scientific purposes we use the single word *temperature*. To attach a definite meaning to it, let us recall the experiment in which a hot coin was placed on a cold one. Heat passed from the former to the latter.

One body is said to be at a higher temperature than another, if, when they are placed in contact, heat passes from

the first to the second. If no heat passes, they are at the same temperature.

Two bodies at the same temperature are also described as in *thermal equilibrium.* Experience shows that any two bodies, placed in contact and protected from gain or loss of heat externally, come to thermal equilibrium. We can now define temperature itself.

Temperature is the condition of a body that determines in what direction heat flows, when the body is in contact with other bodies.

When is one body at a higher temperature than another? Explain the term thermal equilibrium. How may two bodies come to thermal equilibrium? Define temperature.

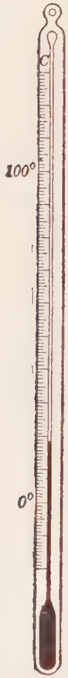


Fig. 185. Thermometer

206. The Mercury Thermometer.—Many properties of bodies change when the bodies are heated or cooled, and any one of these properties might be used as a means of testing temperatures. Different properties have, in fact, been used, but the one most commonly used is volume, especially the volume of mercury contained in a glass *bulb* with a fine glass tube or *stem* attached (Fig. 185). Very minute changes in the volume of the mercury produce large changes in the level of the mercury in the tube. By bringing the bulb into close contact with various bodies and observing the heights of the mercury, we can classify these bodies as regards temperature. But we cannot *measure* temperature until we choose a unit and draw up a *scale* to be attached to the stem or engraved upon it. When so equipped the apparatus becomes a *thermometer* or instrument for ascertaining temperature.

What simple means may be used to give an idea of the temperature of a body? What is a thermometer? Describe one.

207. Fixed Points of a Thermometer.—To construct a scale for a thermometer, we first fix on two temperatures and assign numbers to them. The two most convenient are the temperature of a mixture of ice and water and that of steam above boiling water. The reason for choosing these two temperatures is that, if we take some precautions, we find them to be invariable and easily reproduced everywhere.

When the bulb of the thermometer is placed in a vessel containing cracked ice, with enough water to fill the spaces between the pieces of ice (Fig. 186), the mercury in the stem always comes to the same height. This we call the *ice-point* on the thermometer.

Again, when the bulb is placed in steam above boiling water in an open vessel, the mercury rises to an invariable height (Fig. 187). This height is found to be the same at all times when the atmospheric pressure, as indicated by the barometer, is the same. If, therefore, we specify that the height of the barometer must be 76 cm. (properly corrected) we shall have a second fixed point on the thermometer. This is called the *steam-point* on the thermometer.

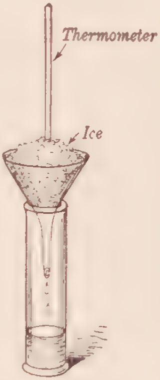


FIG. 186. Determining the Ice Point of a Thermometer

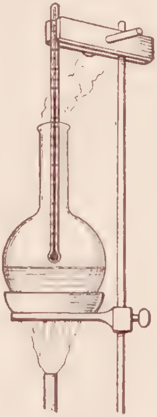


FIG. 187. Determining the Steam Point of a Thermometer

The terms "freezing point" and "boiling point" are often used instead of ice-point and steam-point, but since it is water that is always employed in calibrating a thermometer the latter two terms are preferable.

To make a thermometer, what is necessary besides the tube and the mercury? How is the ice-point on the thermometer obtained? How is the steam-point obtained? Why are these two points chosen?

208. The Centigrade Scale.—The distance between the fixed points on a thermometer is too great to serve as a convenient unit for measuring temperature. By dividing it into 100 parts and calling each part a *degree,* we get what is called the *Centigrade scale* of temperature. The ice point is called the *zero* of the scale and is marked 0°. The steam point is marked 100° (Fig. 188).

A thermometer so constructed would not enable us to measure temperatures higher than the boiling point of water or lower than the melting point of ice. Hence the scale is extended above and below these points with divisions of the same size as between them. The total number of degrees shown on the tube will depend upon the length and bore of the tube, and the size of the bulb.

How are the ice-point and the steam-point marked on the Centigrade thermometer? How is the space between them divided? How are temperatures above and below these points found?

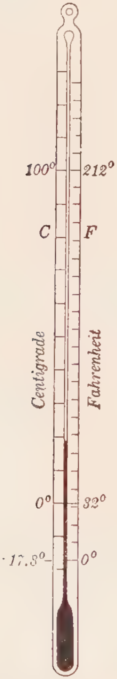


FIG. 188. Centigrade and Fahrenheit Scales

209. The Fahrenheit Scale.—Another scale for finding the temperature of the air is in common use in English speaking countries. Fahrenheit, who devised it, chose for his lower fixed point the temperature of a mixture of ice and salt. This he marked 0°. For the upper fixed point he selected the temperature of the human body. With this scale, the temperature of melting ice is 32°, and that of boiling water 212°, so that there are 180 degrees between them. (The normal temperature of the human body is about 98.4°.)

To find the relation between the two scales, let us suppose that both are engraved on a thermometer (Fig. 189). From the ice-point to the steam-point there are 100 Centigrade degrees and 212 — 32, or 180 Fahrenheit degrees. Hence between any two temperatures there are 5/9 as many Centigrade as Fahrenheit degrees. From the ice-point to the top of the mercury there are C Centigrade degrees and $(F - 32)$ Fahrenheit degrees. Hence

$$C = \frac{5}{9}(F - 32). \qquad F = \frac{9}{5}C + 32$$

What are the corresponding points marked on the Fahrenheit scale? How did Fahrenheit determine these points? How large is a Centigrade degree in terms of Fahrenheit degrees? How may a temperature on the Fahrenheit scale be converted to the corresponding Centigrade temperature? How may the reverse change be made?

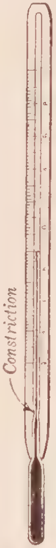


FIG. 189. Maximum Thermometer

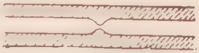


FIG. 190. Constriction of Maximum Thermometer

210. Special Liquid Thermometers.—It is often desirable to know how high the temperature has been since a certain time. *Maximum thermometers* are made with a constriction (or irregularity) in the bore, just above the bulb (Fig. 189). When the mercury in the bulb expands, the mercury flows through the constriction, but when the mercury begins to contract, the column of mercury breaks at the constriction, so that the mercury in the stem does not run back into the bulb. Thus the top of the mercury shows the highest temperature reached. This is the principle made use of in the physician's *clinical* thermometer and in the Weather Bureau's maximum thermometer. (Fig. 190.)

FIG. 191. Minimum Thermometer

Mercury freezes at — 38.9° C. Hence for weather purposes at lower temperatures thermometers with alcohol (or pentane or toluol) are made. *Minimum* thermometers (Fig. 192) are usually alcohol thermometers, in which there is a small glass index; this is pulled back by the contraction of the alcohol, but the expanding alcohol flows by without moving it.

Mercury thermometers can be made for use up to the temperature at which the mercury would boil, which is 357° C. or 675° F. (Fig. 192). For higher temperatures, thermometers are made with a small amount of a gas in the tube above the mercury. The pressure of this gas keeps the mercury from boiling. For still higher temperatures, quartz is used instead of glass for the thermometer tube, as it does not soften so readily, and so mercury thermometers reading up to 700° C. can be constructed. For very much higher temperatures, such as those of furnaces, other properties of bodies, for example the electrical resistance of wires, are made use of for measuring temperatures.

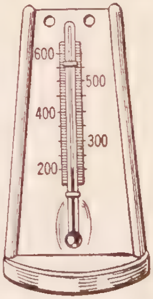


FIG. 192. Oven Thermometer

What is a maximum thermometer? How is it made? Why does it show the highest temperature since it was set? What is a clinical thermometer? A minimum thermometer? How does it operate?

211. Distinction between Heat and Temperature.—It is clear from what has been stated that there is a close relation between heat and temperature, but the meanings of the two terms must be carefully distinguished. There is a similar distinction between many other pairs of terms. No one is likely to confuse the words sugar and sweetness. To make the water which fills a cup and that which fills a teakettle equally sweet requires very different quantities of sugar. So, too, it requires very different amounts of heat to make them equally hot, that is, to raise them to the same temperature. The water in the cup can be quickly brought to boiling over a small gas flame, while it may take a large fire a longer time to make the water in the teakettle boil. A lighted match is at a temperature high enough to burn the hand, but the quantity of heat it gives off will not appreciably warm the room.

We may put the matter in another way. We have seen that the heat in a body is the total molecular kinetic energy in the body. Now at any moment some of the molecules in the body are moving faster than the average and have greater kinetic energy than the average, and some are moving more slowly and have less than the average kinetic energy. The temperature of the body is a measure of the *average kinetic energy of the molecules.* This is quite different from their total kinetic energy, just as the average wealth of the people in a state is very different from the total wealth of all.

Is heat the same thing as temperature? Give illustrations to explain what you mean. Do two bodies at the same temperature necessarily contain the same amount of heat? Give an improved definition of heat.

EXERCISES

1. How do we determine the temperature of a body?
2. What fluid is most commonly used for the fluid in thermometers and why is it chosen?

3. Why is it necessary that the bore of a thermometer tube should be of uniform diameter?

4. What effect on the scale of a thermometer would a large bulb have? A small bulb?

5. What are the fixed points on a Fahrenheit thermometer? On a Centigrade thermometer? Which is the more sensitive?

6. Why is it necessary to have fixed points on thermometers?

7. Why is the bulb of a thermometer usually made cylindrical instead of spherical?

8. Why is alcohol used in some thermometers?

9. How does a maximum thermometer record? A minimum thermometer?

10. What is the difference between the terms temperature and heat?

PROBLEMS

1. Change 0° F. to C., 5° F. to C., 10° C. to F., —10° C. to F.

2. At what temperature do Centigrade and Fahrenheit thermometers read the same?

3. A temperature of —273° C. is called "absolute zero." What is it on the Fahrenheit scale?

CHAPTER XXII

EXPANSION OF SOLIDS

212. Effects and Uses of Expansion.—Expansion due to heating and contraction due to cooling are usually very small, but they often have very important effects and uses. To permit expansion, one end of a steel girder bridge is supported on rollers. The changes of length of the Forth bridge, near Edinburgh, Scotland, amount to about 6 ft. In laying a railroad line, spaces, to allow for expansion, must be left between the rails. For the same reason hot water pipes and steam pipes are joined together with telescopic joints (Fig. 193). Bolts to hold boiler plates together are riveted in place while hot; on cooling they draw the plates together. Steel tires are fitted on wheels while hot, and bind the wheels firmly when cold. Bulging walls of buildings are sometimes drawn back by rods, tightened while hot and permitted to cool, so the contraction of the rods pulls the walls into place.

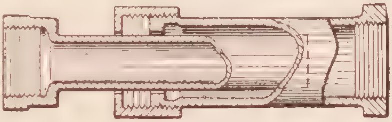


Fig. 193. Expansion Joint

The metal cover of a preserve jar may be on so tight that it cannot be twisted off, but hot water will make it expand and loosen it. Hot water poured into a cold glass bottle usually cracks it, owing to the strain caused by the sudden expansion of the inner surface of the glass. This will not happen if the bottle is warmed slowly.

What effect does heat have on the length of most bodies? Mention various means taken to allow for this effect. What practical uses can be made of this effect? Why is a cold glass apt to be broken by having hot water poured into it? How can this be avoided?

213. Measurement of Expansion.—When a rod is heated, there is usually no visible change in its length. Some means of measurement more sensitive than the eye is needed. We shall not try to describe the very accurate instruments used for this purpose, but a simple experiment will show that the expansion is not too small to be measured.

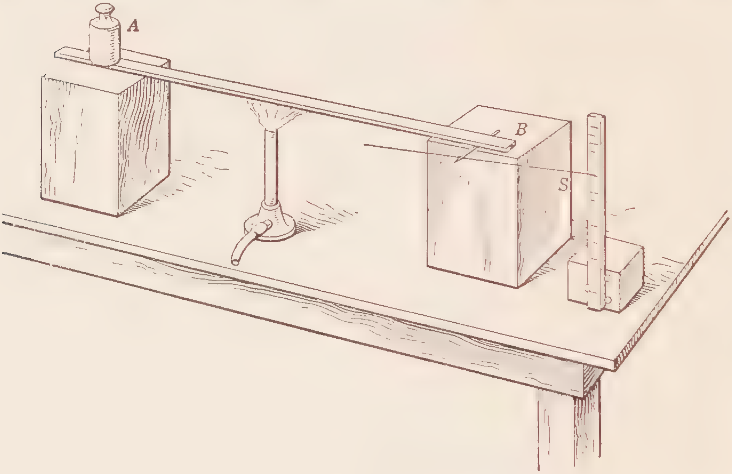


FIG. 194. Expansion of Metal Bar

AB (Fig. 194) is a flat bar, of which one end *A* is kept fixed by a heavy weight, while the other end, *B*, rests on a sewing needle. The needle lies on a smooth horizontal surface, such as a piece of plate glass. A straw, *S*, on the end of the needle, acts as an index to show the slightest movement of *B*. If a gas burner, or even a lighted match, be held beneath the bar, the motion of the straw will show that the bar has increased in length. When the flame is removed, the contraction of the bar, as it cools, will be shown by the straw turning in the opposite direction.

Why can we not usually see the expansion of a body when heated? Describe a simple arrangement for making visible the expansion of a rod. What happens when the rod is cooled?

214. Expansion of Different Solids.—If the last experiment were tried with bars of iron, copper, brass, wood, etc., they would also be found to expand, but by different amounts, when heated. For equal lengths and equal rises of temperature, brass expands one-half more than steel, and aluminum nearly twice as much.

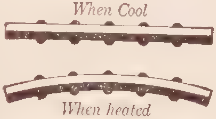


FIG. 195. Unequal Expansion

If two rods of different materials be riveted together and heated, bending will take place (Fig. 195), a proof of the unequal expansion of the metals. This is the basis of a type of thermometer for showing when a room is too hot or too cold. On bending too far in either direction the double bar (Fig. 196) closes an electric circuit and rings the bells. A bar of brass joined to one of hard rubber is commonly used in *thermostats* for keeping a constant temperature in rooms, incubators, etc. In the *oven thermometer* spiral strips of two different metals are riveted together (Fig. 197). This tends to straighten out when heated, and an index attached to it shows the temperature. The ordinary metallic thermometer is shown in figure 197.

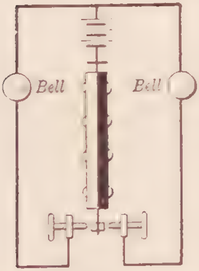


FIG. 196. Principle of Thermostat

A clock pendulum can be made of invariable length by constructing it of alternate bars of brass and steel. These are joined together in such a way that the expansion of one metal lowers the bob as much as that of the other raises it (Fig. 198).

The balance wheel of a watch (Fig. 199) is kept oscillating by the force exerted by the hairspring and its rate of oscillation determines the rate of the watch. When the temperature rises the elasticity of the spring weakens slightly. This would cause the wheel to move more slowly, and the watch would lose time. To compensate this, the rim of the wheel is made of two strips of different metals fastened together, so that it bends inward when heated. The resistance to oscillating that it offers because of its inertia is then reduced, and the rate of the watch remains unchanged.

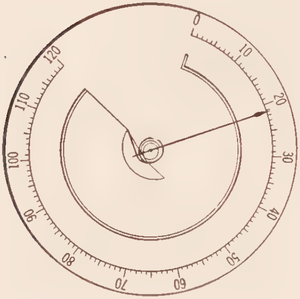


Fig. 197. Principle of Metallic Thermometer

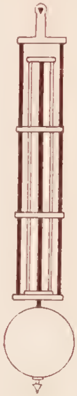


Fig. 198. Clock Pendulum

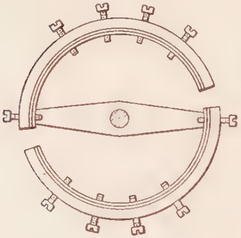


Fig. 199. Balance Wheel

Do all substances expand alike when heated? Which expands more, brass or iron? Aluminum or steel? How can this unequal expansion be made useful? What is a thermostat? What substances are used in a thermostat? How are oven thermometers made? How may the lengthening of a pendulum with heat be prevented?

215. Coefficient of Linear Expansion.—Expansion due to heating must frequently be calculated and allowed for, as, for example, in designing large steel buildings. One well ascertained fact simplifies such calculations. If a solid expands a certain amount when heated one degree, it will expand twice as much when the rise is two degrees, three times as much when the rise is three degrees, and so on. In other words, **the expansion of a solid is proportional to its rise of temperature.*** Hence we need to know how much each unit of length of the solid expands when its temperature is raised one degree. **The change of length, per unit length, per degree, is called the coefficient of linear expansion of a solid.**

COEFFICIENTS OF LINEAR EXPANSION

Aluminum	.000023	Iron	.000012
Brass	.000019	Lead	.000029
Copper	.000017	Platinum	.000009
Ebonite	.000084	Tin	.000022
Glass	.000009	Zinc	.000029

The values given in this table are for the Centigrade degree. To find the coefficients of expansion for the Fahrenheit degree, multiply the above values by 5/9.

With the aid of this table we can readily calculate expansions due to heat. For example, let us find the expansion of a rod of brass one meter long when heated 50 degrees. Each cm. expands .000019 cm. for each degree rise of temperature, or $.000019 \times 50$ cm. for 50 degrees rise. Hence the whole rod expands $100 \times .000019 \times 50 = .095$ cm. Expansion, e, equals the product of length, l, coefficient of expansion, a, and rise of temperature, t;

$$\mathbf{e = lat}$$

What fact underlies all calculations regarding expansion? In order to calculate the expansion of a given substance, what must we know about that substance? Define coefficient of linear expansion of a solid. Is the value of this coefficient the same for all solids? How is this coefficient used in calculating expansion? State the formula used in such calculations.

---

* In very great changes of temperature the relation between expansion and temperature is not so simple, but this is a minor effect, which we need not consider here.

216. Some Bodies Contract when Heated.—An experiment for testing whether rubber expands or contracts when heated may be performed as follows: A pointer is fixed to a stretched rubber tube in such a way that an increase in the length of the tube would be shown by an upward motion of the end of the pointer. If now the tube is heated by passing a current of steam through it, the end of the pointer *falls*, showing that the rubber contracts when heated. This exceptional action of rubber is in reality due to an increase in its elasticity (§ 18) when it is heated. (Fig. 200.)

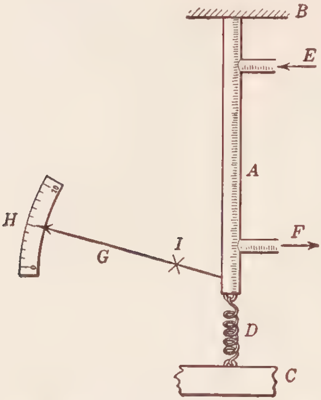


FIG. 200. Rubber Contracts When Heated

A is rubber tube stretched between supports, *B* and *C*, by spring *D*. Steam goes in at *E* and out at *F*. *G* is a pointer that moves over scale *H* as tube grows shorter. *I* are supports to keep pointer in place.

Do all substances expand on being heated? Mention an exception. What really causes the contraction of the rubber?

217. Cubical Expansion. — Thus far we have supposed the solid to be in the form of a rod, and have spoken of change of length only. But the other dimensions change in the same way. A copper sphere that will just pass through a ring, when both are at the same temperature, will not pass if it is first heated (Fig. 201). The sphere becomes a larger sphere when heated.

The change of volume of each unit cube of a substance when its temperature is raised 1 degree is called the coefficient of cubical expansion of the substance. Let us denote it by *A*. Since each unit of volume of the body increases by *A* when heated one degree, it follows that, if the volume before heating be V, and if the rise of temperature be t degrees, the total increase of volume will be VAt. Denoting the increase of volume by E,

$$\mathbf{E = VAt.}$$

Do solid bodies change their volume when heated? Describe an experiment to prove your statement. Define coefficient of cubical expansion. Give the formula for computing the increase of volume of a solid.

218. Relation between Cubical and Linear Expansion.—When a cube of unit side is heated one degree, each side increases from a length 1 to a length $1 + a$. Hence its volume becomes $(1 + a)^3$ or $1 + 3a + 3a^2 + a^3$. Since a is always very small (Table § 215), $3a^2$ and a^3 are too small to be worth considering. Hence the increase of volume of the unit cube when its temperature is raised one degree is $3a$. The coefficient of cubical expansion of a substance is therefore equal to three times its coefficient of linear expansion, or

$$A = 3a.$$

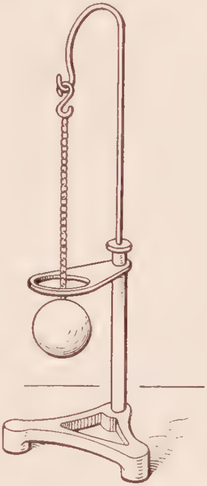


FIG. 201. Cubical Expansion

How may the coefficient of cubical expansion be computed from the coefficient of linear expansion? Prove this.

219. Expansion of Flasks.—It is sometimes necessary to know the capacity, or internal volume, of a flask when heated. The capacity of the flask is always the same as the volume of a block of the same material as the flask and of such a size as just to fill the flask. The changes of volume of this block can be calculated from its initial volume and its coefficient of cubical expansion together with its rise of temperature. This also gives the change of capacity of the flask.

Is the volume of a flask changed by heating it? How could you find how much more it would hold when hot?

EXERCISES

1. Why is glass apt to crack when suddenly heated? Why does this happen less often when the heating is slow?

2. It is said that a silver spoon placed in a preserve jar before hot liquid is poured in, will prevent the jar's cracking. To what extent is this true? Explain.

3. Secure a set of directions for preserving fruit and explain the various expedients given to prevent the cracking of the containers.

4. Why are glass chemical utensils, such as beakers and test-tubes, made thin?

5. The Brooklyn Bridge cables are shorter in winter than in summer. Explain.

6. Why do they not cast the top of an ordinary coal stove in one piece?

7. Suggest a method for removing a glass stopper from a bottle, when it has stuck fast.

8. Study the construction of a vent valve on a steam radiator and explain its operation.

9. Examine the balance wheel of a medium priced watch, and explain its construction.

PROBLEMS

1. The coefficient of expansion of iron is 0.000012. If a mile of telegraph wire is stretched when the temperature is 0° C., what will be the length of the wire when the temperature is 22° C.?

2. An iron rod is 2 m. long at 20° C. What is its length at 0° C.?

3. A driving wheel of a certain locomotive is 72 inches in diameter at 0° C. How much farther will the engine be carried per 1000 revolutions of the wheel when the temperature is 25° C.?

4. A 100 ft. steel tape is correct at 20° C. What correction will have to be made in a measured distance of a mile when the temperature is 0° C.?

CHAPTER XXIII

EXPANSION OF LIQUIDS

220. Expansion of Different Liquids.—To find whether two liquids, such as alcohol and water, expand equally when heated, fill a test tube (Fig. 202*a*) with colored water and close it with a rubber stopper, through which a glass tube, at least two feet long, is thrust. Press the stopper into the test tube, until the water rises an inch or two in the tube. Fill a similar tube with colored alcohol, so that the levels of the liquids are the same in the two tubes. Now plunge both test tubes into a beaker of hot water. The rise of each liquid shows its expansion, but it will be noted that the alcohol expands much more than the water.

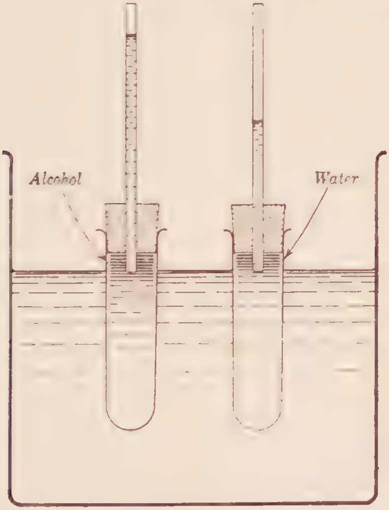


FIG. 202*a*. Expansion of Liquids

The large expansion of alcohol and its low freezing point (—130° C.) make it suitable for use in thermometers for low temperatures.

Do liquids expand when heated? Do they all expand alike? How can this be shown? Which expands more, water or alcohol? Why is alcohol used in thermometers for low temperatures?

221. Real Expansion and Apparent Expansion of Liquids. —The rise of level in the tubes in the last experiment is not a measure of the real expansion of the liquids; for we have not taken account of the expansion of the test tubes, which tends to lower the levels of the liquids in the tubes.

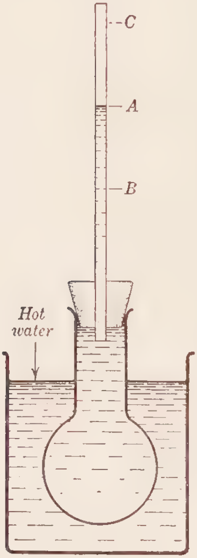


FIG. 202*b*. Real and Apparent Expansion of Liquids

Figure 202*b* shows an apparatus in which the test tubes have been replaced by a flask. Let the level of the liquid be at first at *A*, 8 or 10 inches above the stopper. If the flask be plunged into hot water, the level of the liquid in the tube will at once fall to *B*, a point several inches below *A*. But it will then begin to rise again, and will finally reach a point *C*, the height of which depends on the temperature of the hot water. The drop from *A* to *B* is due to the expansion of the flask, which is heated and expands before the liquid within it expands. The rise from *B* to *C* is due to the heating and expansion of the liquid. Thus the *real* expansion of the liquid, as indicated by *BC*, is greater than its apparent expansion, as shown by *AC*.

FIG. 203. Compensation by mercury

From the above it is clear that we can find the real expansion of a liquid by first finding its apparent expansion, and then adding the expansion of the vessel, which can be calculated from its volume and coefficient of expansion.

In the form of clock pendulum shown in figure 203 the upward expansion of the mercury compensates the downward expansion of the iron rod when the temperature rises, so that the effective length of the pendulum remains constant.

In figure 202*b*, why does the level of the liquid first fall when the flask is placed in hot water? Why is this fall not permanent? How can the expansion of a liquid be found?

222. Coefficient of Expansion of a Liquid.—In speaking of the expansion of a solid, we had to distinguish between linear and cubical expansion. But such terms as length and breadth are not useful in describing a liquid, since it takes the shape of the containing vessel. Hence in speaking of the expansion of a liquid, we shall mean its change of volume. **The coefficient of expansion of a liquid is its change of volume per unit volume per degree rise of temperature.**

Define the coefficient of expansion of a liquid.

COEFFICIENTS OF EXPANSION OF LIQUIDS

Substances	Coefficient of Expansion
Alcohol	.00110
Benzine	.00124
Mercury	.00018
Petroleum	.00090
Water (15° — 100°)	.00027

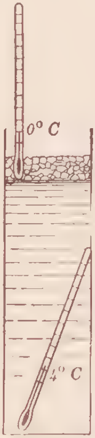


FIG. 204*a*. Water is densest at 4° C.

223. The Expansion of Water.—Water, the most widespread and important of liquids, shows very peculiar changes of volume when heated. As its temperature is raised from 0° C. to 4° C., it shrinks in volume, while from 4° C. upwards it expands. This peculiarity forbids the use of water in thermometers.

In a tall beaker containing water and some ice (Fig. 204*a*) the temperature of the water in contact with the ice at the top is 0° C. and the temperature of the water at the bottom is about 4° C. From this it is evident that the density of water is greater at 4° C. than at 0° C.

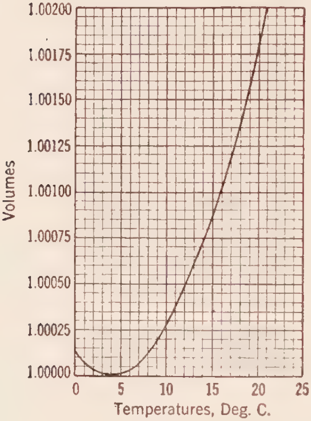


FIG. 204*b*. Relation between Temperatures and Volumes of Water

Figure 204*b* shows at a glance the way in which the volume of water changes as its temperature rises, and it also shows the readings that a water thermometer would give from 0° C. to 22° C. The scale would doubleback on itself, so that there would be nothing to indicate whether the temperature was 2° C. or 6° C.

What change takes place in water when it is heated from 0° C. to 4° C.? From 4° C. to higher temperatures? Why is not colored water a suitable liquid for use in a thermometer?

224. Point of Maximum Density of Water.—As the volume of water decreases from 0° C. to 4° C., its density necessarily increases. Above 4° C. the density decreases, since the volume increases. Hence water has a maximum density at 4° C. The actual variations of density are very small. If the density of water at 4° C. is taken as unity, its density at 3° C. is .999999 and at 0° C. it is .999878. Slight as these variations are, we shall see later that they are of very great importance in Nature.

What changes in density occur when water is heated from 0° C. to higher temperatures? At what temperature is the water the densest? Are these slight changes of any importance?

EXERCISES

1. Why is the bore of a thermometer made so exceedingly small?

2. If the bulb of a thermometer is plunged into hot water, the mercury first falls. Why?

3. Why is it difficult to measure the real expansion of a liquid?

4. Why would water not be suitable as the liquid in a thermometer?

PROBLEMS

1. A certain heating plant system holds 6:5 cu. ft. of water at 15° C. Neglecting the expansion of the container, what will be the volume of the water at 80° C.?

2. If a cubic foot of water at 0° C. weighs 62½ lbs., what will a cubic foot of water at 100° C. weigh?

3. If a tank contains 1000 gallons of petroleum at 0° C., what will its volume be at 30° C.?

CHAPTER XXIV

EXPANSION OF GASES

225. Expansion of Air.—While the expansion of a solid or liquid is so small that it is not readily made visible, that of a gas is large and is readily shown.

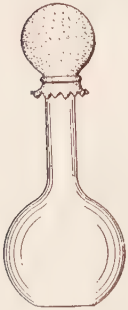


Fig. 205. Expansion of Gases

Tie a sheet of thin rubber (Fig. 205) over the mouth of a large glass flask and warm the flask in a flame. The air within will expand rapidly, causing the rubber to bulge outward.

In the apparatus shown in figure 206, the bulb contains air, and the open end of the tube dips into water. If the bulb be warmed by the hand, the air will expand and drive the water down in the tube. When the hand is removed, the air contracts and allows the atmospheric pressure to drive the water up again. This was, in fact, the first form of thermometer. It was invented by Galileo, but it had the disadvantage that changes in the pressure of the atmosphere also caused changes in the level of the water in the tube.

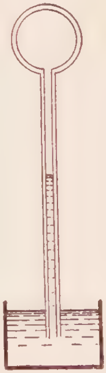


Fig. 206. Air Thermometer

From this it is evident that we cannot make any clear statements as regards the expansion of a gas, unless we agree that the pressure shall remain constant. For, when the pressure as well as the temperature changes, part of the change of volume is due to the change in pressure.

Is the expansion of gases when heated greater or smaller than that of solids? Of liquids? How may the expansion of air be made visible? What difficulty arises in measuring the expansion of gases by heat? What effect do changes of pressure have on the volume of a gas?

226. All Gases Expand Equally.—If we start with equal volumes of any two different gases and raise their temperature by equal amounts, the pressure being kept constant, their new volumes are also equal. Hence **all gases expand equally when heated.** In this respect gases differ very much from solids and liquids.

In what important way does the expansion of gases differ from that of liquids and solids?

227. Coefficient of Expansion of a Gas.—Figure 207 represents a tube about 30 cm. long, the bore being 1 mm. in diameter or less. At the bottom there is a drop of sulphuric acid to keep the air dry. At *B* there is a pellet of mercury, which confines a quantity of air in the part *AB* of the tube.

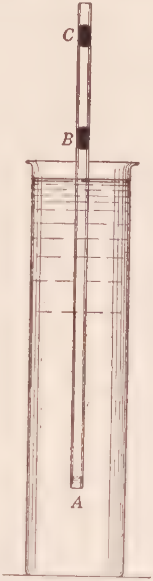


FIG. 207. Coefficient of Expansion of Gases

Dip the tube into ice-water and mark the position of the bottom of the pellet *B*. Measure the length *AB*. Now surround the tube with steam from boiling water. The expansion of the air will drive the pellet to *C*. Measure the length of *AC*.

The bore of the tube is practically uniform, and the expansion of the tube is very slight compared with that of the air. Hence the volume of the air inclosed is proportional to the length of the air column. BC represents the increase of the volume of the air when it is heated from 0° C. to 100° C. If BC be divided by 100 and again by AB, the result will be the coefficient of expansion of air.

The coefficient of expansion of a gas is the increase in volume of a unit of volume of the gas at 0° C. when the temperature is raised one degree, the pressure being kept constant.

When experiments like the above are made with great care, it is found that the coefficient of expansion of air is .003665 or 1/273. The figure is very slightly different for other gases, but we shall neglect these differences.

Hence when a quantity of gas, the volume of which is V_0 at 0° C., is raised to 1° C., the increase of volume is 1/273 of V_0; when it is raised from 0° C. to 2° C., the increase of volume is 2/273 of V_0; and so on. In each case the pressure is supposed to be kept constant. To make the statement more general, let the rise of temperature be from 0° C. to t° C. The increase of volume will then be $t/273$ of V_0 or $V_0t/273$. Hence the whole volume at t° C. will be $V_0 + V_0t/273$ or $V_0\ (1 + t/273)$, and if we denote the volume at t° C. by V,

$$V = V_0 \left(1 + \frac{t}{273}\right)$$

$$\frac{V}{V_0} = \frac{273 + t}{273}$$

Describe an experiment for determining the coefficient of expansion of a gas. From the readings obtained how would you compute the coefficient? Define coefficient of expansion of a gas. What is the value of the coefficient? Is it exactly the same for all gases? Give the formula for finding the expansion of a gas due to heat.

228. Absolute Zero.—From the formula just stated, it is easy to calculate the volume of a quantity of gas at any temperature t° C., when its volume at 0° C. is known. The first step is to add 273 to t. Now this is equivalent to making a change in the zero of our thermometers. If, after laying off 100 divisions between the ice-point and the steam-point, we should mark the ice-point 273, the steam-point would become 373, and every reading would be increased by 273. The new zero would be 273 degrees below the ice-point (Fig. 208).

This temperature, 273 degrees Centigrade below the ice-point, is called the absolute zero, and temperatures reckoned from it are called absolute temperatures. Absolute zero is the lowest temperature possible. A body at that temperature would contain no heat, for its molecules would be reduced to rest.

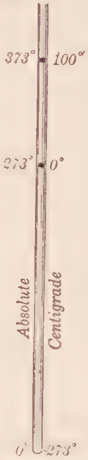


Fig. 208.

You may also think of absolute zero in the following way. A tube that is closed at the lower end (Fig. 207) contains air up to a height of 273 mm, with a drop of mercury above the air. The tube is at first at 0° C. If it is then heated one degree the drop of mercury will rise to 274 mm. If the heating be continued to 100° C. the drop will rise to 273 + 100 = 373 mm. If we start again at 0° C., and cool the tube one degree the air column will shorten by 1 mm, and so on. Hence if we could cool the tube to —273° C., and if the air still remained a gas, its volume would shrink to zero volume. Since the volume of the air could not be less than zero, the lowest temperature possible is —273° C.

What number is added to the Centigrade temperature in calculating the expansion of a gas? Define absolute zero. Absolute temperature. What would be the condition of the molecules of a gas at absolute zero?

229. Charles' Law.—If the temperature of a body, as read by an ordinary thermometer, is $t°$ C., and if we denote the absolute temperature of the body by T, then $T = t + 273$. We can now change the formula for calculating the volume of a gas to the simpler form

$$\frac{V}{V_0} = \frac{T}{273}$$

If we heat the gas, V and T will change in the same proportion, since V_0 and 273 are constants. Hence, *when the temperature of a gas is changed, the pressure being kept constant, the volumes are proportional to the absolute temperatures.* This is called *Charles' law.* It means that if V is the volume of a quantity of gas at absolute temperature T, and V' its volume at absolute temperature T',

$$\frac{V}{V'} = \frac{T}{T'}$$

State Charles' law. Give the formula which expresses it.

230. Increase of Pressure of a Gas.—Thus far we have been supposing that the pressure on the heated gas has been kept constant, while its volume increases. But it is equally important to know how the pressure will change if the heated gas is not allowed to expand. For example, what happens when the temperature of a balloon, filled with hydrogen, or of an auto tire, filled with air, is changed?

Very careful experiments have shown that, when the volume of a gas is kept constant, the pressure increases by 1 part in 273 for each rise of temperature of one degree reckoned from 0° C.

The remarkable recurrence of the fraction 1/273 should be noted. Whichever of the two, volume or pressure, we choose to keep constant, the rate of increase of the other is the same, namely, 1 part in 273 for each degree rise of temperature from 0° C. Hence it is evident that:

When the temperature of a gas is changed, the volume being kept constant, the pressures are proportional to the temperatures reckoned from absolute zero. If the pressure of the gas is P when it is T degrees above absolute zero, and P' at T' degrees above absolute zero,

$$\frac{P}{P'} = \frac{T}{T'}$$

In a *gas thermometer* (Fig. 209) the relation between the pressure and temperature of a gas, when its volume is kept constant, is used for measuring temperature. A hydrogen thermometer has a bulb that contains hydrogen and a mercury pressure-gauge for finding the pressure of the hydrogen. The temperature T of the bulb at any time is calculated from the pressure P of the hydrogen by the above equation, P' being the pressure when the bulb is in melting ice and T' being 273. Such a thermometer can be used up to the temperature at which glass softens and down to that at which hydrogen becomes a liquid (—243° C.). For accurate scientific purposes temperature is really *defined* by a hydrogen thermometer, rather than by mercury thermometers, which are apt to differ a little among themselves, if different kinds of glass are used.

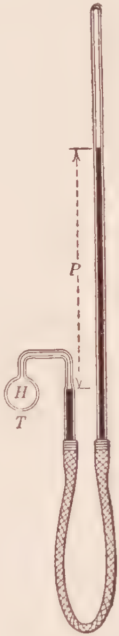


Fig. 209.
Gas Thermometer

If the volume of a gas is kept constant while it is heated, what happens? How much does the pressure increase for each Centigrade degree? State the law involved in this change. Give the formula for computing the change in pressure. What is a gas thermometer? What are its advantages?

231. When Both Pressure and Volume Change.—It often happens that, when a gas is heated, both pressure and volume change. In this case the effect of the heating is shared between them, neither getting as much as if the other took none. When the bulb of Galileo's thermometer (Fig. 206) is warmed by the hand, the air expands, and its pressure increases, as is shown by the shortening of the column of liquid in the tube. A balloon is often sent up only partly inflated. As it rises in the air, temperature, volume, and pressure all change. The gases produced by the explosion of gun-powder in a cannon expand, cool, and fall in pressure. The air above a bonfire rises, expands, and decreases in pressure.

Although the circumstances seem much more complex than in the simpler cases of constant pressure or constant volume, a formula of almost equal simplicity will apply to them. If the gas has a volume V and a pressure P at temperature T (reckoned from absolute zero), and if the volume becomes V' and the pressure P' when the temperature is changed to T',

$$\frac{\mathbf{PV}}{\mathbf{T}} = \frac{\mathbf{P'V'}}{\mathbf{T'}}$$

This formula includes both of the others. For, if the pressure does not change, $P = P'$ and the formula becomes the same as that in § 229. If the volume is constant, $V = V'$ and we get the formula in § 230. This formula also includes Boyle's law (§ 70), as is readily seen by putting $T = T'$. It is therefore called *the general gas law.*

Do both volume and pressure ever change when a gas is heated? Give examples of these effects. Give the formula which includes all the variables involved when a gas is heated. Does this formula involve Charles' law? Boyle's law? State the formula for the general gas law.

EXERCISES

1. What change takes place when a closely stoppered bottle containing air is taken from a cold room into a hot room?

2. What effect has heating a room on the density and the mass of air in the room?

3. From what you have learned as to the real nature of heat explain why a gas exerts greater pressure when it is heated.

4. Which would be more sensitive, an air thermometer or a mercury thermometer with the same size of bulb and the same size of bore?

5. What do you mean by absolute zero? What would be the molecular condition of a body at absolute zero?

6. Which would exert greater pressure when heated, oxygen or hydrogen?

PROBLEMS

1. A balloon contained when full 300,000 cu. ft. of hydrogen. The temperature was 15° C. The temperature became 25° C. What volume of gas escaped?

2. An automobile tire had a volume of 900 cu. in. It was pumped up to a pressure of 75 lbs. per sq. in., when the temperature was 18° C. When moved into the sun the temperature became 35° C. and the tire exploded. What was the volume of the air after its release?

3. A steel tank was filled with hydrogen at a pressure of 225 lbs. per sq. in., when the temperature was 10° C. The tank was taken into a boiler room where the temperature was 34° C. What was the pressure of the gas in the tank?

4. The dimensions of a Physics recitation room are 10 m. by 12 m. by 4 m. The barometer reads 74 cm., and the temperature is 20° C. The density of air under standard conditions is .00129. What is the mass of the air in the room?

CHAPTER XXV

MEASUREMENT OF HEAT

232. Need for a Unit of Heat.—In buying coal, gas, or any fuel, we are buying heat to warm our houses, cook our food, and enable steam engines and gasoline engines to do their work. It is therefore necessary to know how much heat we can get from fuel. Hence we must have a unit of heat for use in measuring heat. This might seem difficult, since heat is not something visible, but a form of energy. But we can measure heat by what it can do, that is, by its effects. The most familiar effect of heat is rise of temperature. If we take some body as a standard, we can say that twice as much heat is required to raise its temperature two degrees as to raise it one degree, three times as much for three degrees, and so on. The most convenient body to use as a standard is a unit mass of water, since water can be obtained fairly pure nearly everywhere. This leads us to a definition of a unit of heat for use in *calorimetry,* which is the scientific term for the measurement of heat.

Why is a unit of heat necessary? What effect of heat is used in measuring heat? What substance is used as a standard for measuring heat? Why is this substance suitable? What is meant by the term calorimetry?

233. Unit of Heat.—*The unit of heat is the amount of heat required to raise the temperature of one gram of water one degree Centigrade.* This is called a *calorie.* It is the unit we shall employ in the measurement of heat.

Engineers usually state masses in pounds and use Fahrenheit thermometers, and they use a larger unit of heat called a *British thermal unit*, usually called, for brevity, a *B.T.U.* of heat. Since a pound = 453.6 grams and a Fahrenheit degree = $\frac{5}{9}$ of a degree Centigrade, one B.T.U. = 453.6 × $\frac{5}{9}$ = 252 calories.

Define calorie. Define British Thermal Unit. Which is greater? How many calories make one B.T.U.?

234. Gain and Loss of Heat.—When a bathtub is partly filled with cold water, and hot water is added to warm the cold water, we assume, without question, that all the heat given up by the hot water goes to the cold water. This is the same thing as saying that the amount of heat in the *mixture* is the sum of the amounts of heat in the two bodies of water before they were mixed. The same principle applies when a hot solid is dropped into a quantity of liquid at a lower temperature. In all such cases the principle that applies is that: **Heat given out equals heat taken in.**

This seems reasonable, but we shall be more certain of it if we remember that heat is a form of energy and is subject to the law of the conservation of energy. This law tells us that, while energy can pass from one body to another, the total amount of energy remains unchanged by the transfer.

When a cold dish is put into hot water what heat exchange takes place? Does the total amount of heat change? If the dish gains 356 calories how many calories does the water lose? Prove your statements by referring to the law of the conservation of energy.

235. Heat and Rise of Temperature.—In measuring heat it is important to know whether two bodies of equal mass, but of different materials, require equal amounts of heat for the same rise of temperature. The following simple experiment is a rough test of this point. *A* in figure 210*a* is a block of copper, in which there is a hole for a thermometer, and *B* is an equal mass of water in a beaker. At start they are at the same temperature, 20° C. If a Bunsen burner is used to heat A, a certain time is required to raise the temperature to 50° C. If the same burner, with the same height of flame, is now placed beneath B for the same length of time, the temperature will only rise to about 23° C. Hence the amount of heat required to raise the block of copper 30 degrees will only raise the equal amount of water about 3 degrees. But this is only a rough test, since some of the heat is used in warming the beaker. We shall see later how a more accurate comparison can be made.

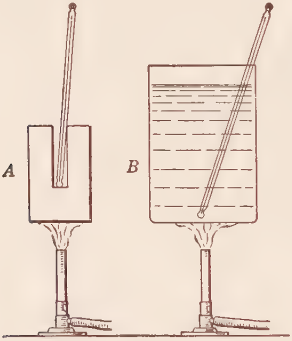


FIG. 210*a*. Specific Heat of Metals

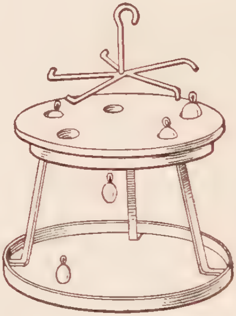


FIG. 210*b*. Specific Heat of Metals

Figure 210*b* shows another method of comparing different substances. Spheres of equal weight of aluminum, copper, iron, zinc, and lead are heated to the same temperature in oil and then placed on a thin cake of paraffin wax. The aluminum melts its way through the wax quickly and the iron less quickly, while the copper, zinc, and lead lag behind. All the spheres fall the same number of degrees in temperature, but they give out different amounts of heat. The aluminum melts its way most quickly through the wax because it gives out most heat and melts most wax. The lead gives out less heat than any of the others and therefore melts less wax.

Describe experiments to prove that different substances require different amounts of heat for equal rises in temperature.

236. Specific Heat of a Substance.—The preceding experiments show, in a general way, how equal masses of different substances differ as regards the amounts of heat they give out or take in as the temperature changes. Before describing a more exact method for measuring this property of substances, we must define the property.

The **specific heat** of a substance is *the number of calories required to raise the temperature of one gram of the substance one degree.* It is, of course, also the amount of heat that a gram of the substance gives out when its temperature falls one degree.

Since the calorie is defined as the heat required to raise one gram of water one degree, it is evident that the specific heat of water is 1. We shall next consider how the specific heat of other substances can be measured.

Do equal masses of water and copper require the same heat to raise their temperatures a given amount? Define specific heat. Describe an experiment to show that specific heats differ. Which has the higher specific heat, aluminum or water?

237. Method of Mixtures.—This is the usual method for finding the specific heat of a substance. (Fig. 211.) The specimen and a quantity of water are brought to different temperatures. They are then put in close contact (or mixed) so that one gives out heat and the other takes this heat in, until they come to a common temperature. From the temperatures and the masses the specific heat is then calculated. The general principle used is that:

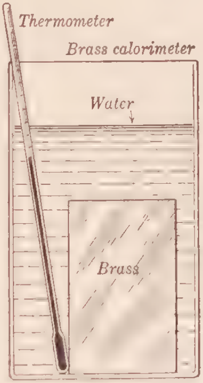


Fig. 211. Specific Heat by Method of Mixture

Heat given out = heat taken in.

The following is the simplest form of the experiment. A block of brass that weighs 500 grams is placed in a light brass vessel, called a *calorimeter,* that weighs 100 grams, and their temperature is found to be 20°. Then 100 grams of water at 40° is poured into the vessel, and after a minute or so to allow all parts to come to a common temperature, this temperature is found to be 32.5°. We can now calculate the specific heat of the brass. The 100 grams of water fell 7.5 degrees and therefore gave up $100 \times 7.5 = 750$ calories. This heat passed into the 600 grams of brass and raised its temperature 12.5 degrees. The heat received by each gram of the brass was $750 \div 600 = 1.25$ calories. Hence the heat required by each gram of brass for a rise of temperature of 1 degree is $1.25 \div 12.5 = 0.1$ calorie. The specific heat of brass is therefore 0.1.

In this example the specimen was supposed to be of the same material as the calorimeter. When the specimen is of different material, it is better to put the water initially in the calorimeter and heat the specimen, and then lower the heated specimen into the calorimeter. The calculation is made as before, by equating heat given out to heat taken in. But there is one difficulty. The heat given out by the heated specimen does not all go to the water. Some of it goes to heat the calorimeter. Because of this we need to know what is called the *water equivalent* of the calorimeter. As an example, we shall suppose that the calorimeter is the brass one used in the first experiment. We found that each gram of brass required .1 calorie for a rise of 1 degree. Hence the 100 grams of brass require 10 calories for a rise of 1 degree. Now 10 grams of water also require 10 calories for a rise of 1 degree. Hence the calorimeter takes as much heat as 10 grams of water would. This number 10 is called the water equivalent of this particular calorimeter. It is found by *multiplying the mass of the calorimeter by the specific heat of the substance of the* *calorimeter.* In calculation it is added to the amount of water in the calorimeter, to take account of the effect of the calorimeter, as if there were that much more water and no calorimeter to be heated. The mass of any body multiplied by its specific heat is the *thermal capacity* of the body. It gives the number of calories required to heat the body one degree.

Example. *A copper block that weighs 485 grams is heated to 96.2° and is then dropped into a brass calorimeter that weighs 100 grams, containing 115 grams of water at 17.6°. The final temperature of the mixture is 38.6°. Calculate the specific heat of copper.*

Water equivalent of calorimeter = 100 × .1 = 10 g.
Heat taken in = (10 + 115) × (38.6 — 17.6) = ... 2625 cal.
Heat given out by 1 gram of copper = 2625 ÷ 485 = ... 5.40 cal.
Heat given out by each gram of copper in falling 1° =
5.40 ÷ 57.6 = ... .094 cal.
Hence the specific heat of copper is .094.

What is the procedure for determining the specific heat of a substance? What interchange of heat takes place? Where does the heat come from? How does the heat given out by the hot body compare with that taken in by the colder one? What is this method called? What is a calorimeter?

TABLE OF SPECIFIC HEATS

Substance	Specific Heat	Substance	Specific Heat
Aluminum	0.214	Alcohol	0.6
Copper	0.094	Mercury	0.033
Ice	0.5	Water	1.000
Iron	0.113	Tin	0.056
Lead	0.031	Zinc	0.095

What things must be multiplied to get the heat received or given out by a body whose temperature is changed? Give the formula. Define the thermal capacity of a body. What is the water equivalent of a body? What is calorimetry?

EXERCISES

1. How do we measure heat? What is the unit? Why was the particular substance that is used as a standard in defining the unit of heat chosen?

2. What is a calorie? A British thermal unit?

3. What is meant by specific heat? Explain the statement that the specific heat of water is 30 times as great as that of mercury.

4. What advantage has the low specific heat of mercury as regards the use of mercury in thermometers?

5. What three things must be known in order to calculate the amount of heat required to warm a body?

6. What is the general principle used in the method of mixture?

7. What is meant by the water equivalent of a calorimeter? How is it calculated?

8. Which will heat more quickly on a stove, a flatiron or a pan of water of the same weight?

PROBLEMS

1. How much heat is required to raise 5 liters of water from zero to the boiling point?

2. If 500 g. of iron at 100° C. are dropped into 400 g. of water at 0° C., what will be the final temperature?

3. How much copper at 200° C. must be mixed with 450 g. of water at 10° C. in order that the final temperature may be 25° C.?

4. A platinum ball weighing 100 g. was placed in a furnace until it had attained the temperature of the fire. It was then dropped into 200 g. of water, the temperature of which rose from 5° C. to 25° C. What was the temperature of the furnace?

5. If a flatiron weighs 4 lb., how many B.T.U. are required to heat it from 60° F. to 300° F.?

6. If coal yields 14,000 B.T.U. per pound when burned, how many tons of water can be raised from the ice-point to the steam-point by burning a ton of coal?

7. In what proportion should hot water at 80° C. and cold water at 10° C. be mixed to give a bath at 40° C.?

CHAPTER XXVI

FUSION

238. Melting and Freezing.—Butter melts in the heat of a hot summer day or in a dish on a hot stove. A plumber with his hot iron melts solder, which gradually hardens as it cools. Iron is put into hot furnaces where it changes to a liquid. This liquid is then poured into cavities which have been made in boxes of sand, and, as it cools, it takes the shape of the molds.

These changes of state are brought about either by adding heat to the bodies or by allowing them to lose heat. It is heat, then, that chiefly determines whether a body shall be in a solid, liquid, or gaseous state.

What change of state occurs in many substances when heated? Is this change reversible? What determines the physical state of a substance?

239. Fusion.—When a body changes from a solid to a liquid, it is said to melt, fuse, or liquefy. In the case of ice, this change takes place at a temperature that is always the same, if the pressure is the same. This is also true of a great many other substances, especially substances which can form crystals. When such a substance is above or below its melting point, heat produces a change of temperature; but when the substance is a solid at its melting point, heat produces a change of state without any change of temperature.

What is meant by fusion? If a body is below its melting point what change takes place when heat is added to it? If it is at its melting point when the heat is added? Does the temperature of the body change while melting?

240. Melting Points.—When a body passes from the liquid to the solid state, it is said to freeze, solidify, or congeal. Usually the liquid freezes at the temperature at which it melts. But this is not always the case. With care, a liquid can be cooled below the melting point without freezing. If water be well boiled to expel all gases, it may be cooled several degrees below 0° C. and still remain liquid. But it is in an unstable state, and a little jarring will cause it to freeze suddenly, and its temperature will become 0°. But ice cannot be raised above the melting point without melting. For this reason it is more definite to speak of the melting point of a substance than of its freezing point.

MELTING POINTS

Helium	—271.5° C.	Lead	327° C.
Hydrogen	—252° C.	Zinc	419° C.
Alcohol	—130° C.	Aluminum	657° C.
Mercury	—39° C.	Cast Iron	1100° C.
Water	0° C.	Platinum	1735° C.
Paraffin	55° C.	Tungsten	3270° C.
Tin	232° C.		

What is meant by freezing a liquid? How is it caused? Do all substances freeze at the same temperature they melt? How may this be shown? Why is the melting point commonly given rather than the freezing point?

241. Change of Volume in Freezing and Melting.—When water freezes in the pipes of the water service, the pipes usually burst. Ice floats on water. Thus it is evident that water expands when it freezes, and ice contracts when it melts (Fig. 212*a*).

Paraffin wax contracts on freezing. This is readily observed by filling a test tube with pieces of the wax, and after melting it, allowing it to solidify. The contraction will cause a depression of the surface.

The process of casting in molds gives very good evidence as to whether a substance expands or contracts on solidifying. When iron is cast, it expands and fills all the crevices of the mold, so that the casting comes out with sharp edges. The same is true of bismuth and a few other substances. But when gold, silver, lead, and most metals are cast, the castings are not sharp, which shows that such substances contract on solidifying. For this reason coins and medals are stamped and not cast.

What change in volume takes place when water freezes? When ice melts? Do all substances behave the same way? When molten cast iron solidifies what change in volume takes place? Of what importance is this change? Why are medals and coins stamped rather than cast?

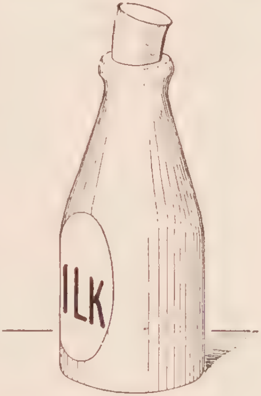


FIG. 212a. Expansion of Milk

242. Force Exerted in Freezing and Melting.—The bursting of water pipes shows the great force that can be exerted by water in freezing. The thickest bombshells can be burst by allowing water to freeze in them. Rocks are torn from cliffs and ledges by the freezing of water in cracks and crevices. Where the ground freezes and thaws with the changes of the seasons, the foundations of buildings must go down below the frost line, to be safe from the effects of repeated expansions and contractions of the water in the soil.

Why do water pipes often burst when the water in them freezes? In what other ways is this effect of importance?

243. Effect of Pressure on Melting Point.—The temperature at which a substance melts varies slightly with the pressure to which it is subjected. Under a pressure of 14 atmospheres ice can be melted at — 0.1° C. This "depression of the melting point" increases as the pressure is increased, but under sufficiently great pressure the melting point begins to rise again.

A beautiful illustration of the effect of pressures is shown in figure 212*b*. A small wire carrying heavy weights will slowly cut through a bar of ice. Owing to the smallness of the area on which the fine wire presses, the pressure just under the wire is very great. Thus the ice is put in a condition in which it can melt, although it is at 0° C. The water formed is squeezed to the upper side of the wire, and freezes again. In skating on ice at about 0° C. a similar effect takes place. The ice melts under the skate, but the water formed freezes again when the pressure is removed. The track of a loaded wagon on snow often shows the same effect.

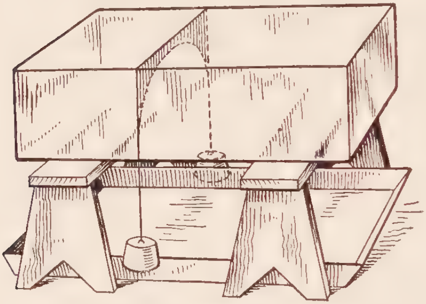


FIG. 212*b*. Regelation Illustrated

If two pieces of ice are pressed between the hands and then released, they will be found to be frozen together. This is called *regelation*. Boys make snowballs in this way; but if the temperature is much below 0° C. the snow will not hold together, until it has been warmed by the heat of the hands. The ice in a glacier melts, where it presses against an obstacle, and thus allows the glacier to move at a slow rate.

Other substances also suffer this change of melting point, when subjected to pressure; but in some the pressure causes a depression of the melting point, and in others an elevation. Substances which, like ice, contract when they melt, have their melting points lowered by pressure, while those which expand on melting have their melting points raised by pressure.

What effect does the pressure have on the melting point of a substance? Is this effect the same for all substances? Explain how the wire cuts its way through the cake of ice in figure 213. Why does the ice freeze together again after the wire passes? Why does the track of a loaded wagon in the snow have a thin glaze of ice upon it? What is regelation? Why is a snow ball made harder by alternately pressing and releasing it? Under what condition does an increase of pressure lower the melting point and under what conditions raise it?

244. Substances with No Definite Melting Points.—Beeswax and glass, when heated, soften gradually, and it is impossible to say just when they become liquid. The same is true of wrought iron, steel, platinum, and many other substances, though in some the change is less gradual than in others.

Plumber's solder, which consists of two parts of lead and one part of tin, is pasty through many degrees of temperature, and it is because of this that the plumber can make "wiped joints."

Do all substances have definite melting points? Mention some examples. Is this softening without definite melting ever useful?

245. Heat of Fusion.—Heat used in melting a substance is often called *latent* (or hidden) heat, since it does not produce a rise of temperature. A better term is **heat of fusion.**

The **heat of fusion,** L, of a solid substance is the **number of calories required to melt one gram of the substance, without change of temperature.** It can be found by the method of mixtures. To measure the heat of fusion of ice, we dry a lump of ice that is at the melting point, and drop it into a measured mass of warm water, the temperature of which has been noted. The heat required to melt the ice is taken from the water, which is therefore cooled. If we now note the temperature of the water at the moment when the ice has all melted, and then re-weigh the calorimeter in order to find the mass of the block of ice, we shall be able to calculate the heat of fusion. To calculate the magnitude of the heat of fusion, we note that the heat given up by the water originally in the calorimeter has been expended in two ways—in melting the ice and in warming the resulting water to its final temperature.

But this experiment does not always give accurate results, since it is difficult to dry the ice completely, and some heat escapes from the calorimeter or comes into it from the outside during the melting. The value obtained when the greatest care is exercised is *79.6 calories per gram* of ice melted (for rough calculations this may be taken as 80). Values obtained for some other substances are given in table below.

Example. *A calorimeter, the specific heat of which is 0.1 and which weighs 100 g., contains 300 g. of water at 55° C. 109 g. of ice are added to the water, and, when all the ice is melted, the resulting temperature is 20° C. Calculate the heat of fusion.*

Heat taken in = Heat given out

The 300 g. of water in falling from 55° to 20° gave out 300 × 35 or	10,500 cal.
The calorimeter in falling from 55° to 20° gave out 100 × .1 × 35 or	350 cal.
Heat given out was	10,850 cal.
The 109 g. of water formed from the ice in warming from 0° to 20° took in 109 × 20 or	2,180 cal.
The heat used in melting the 109 g. ice was	8,670 cal.

Therefore to melt one gram of ice required

$$8670/109 = 79.5 \text{ cal.} = L.$$

HEATS OF FUSION

Aluminum	77	Mercury	3
Copper	43	Platinum	27
Ice	79.6	Sulphur	9
Lead	5	Zinc	28

Define heat of fusion. What becomes of the heat applied while a body is melting? How may the heat of fusion be measured? Why does water become cooler when ice is placed in it? How great is the heat of fusion of ice? What value is commonly used? In the experiment outlined, what two substances furnished the heat which melted the ice? How was the total quantity of heat calculated?

246. Freezing Mixtures.—If 30 grams of common salt be thoroughly mixed with 100 grams of chipped ice or snow, the mixture will become a liquid at a temperature below the melting point of ice. The salt and the ice tend to combine. In the process the ice melts and the salt dissolves in the water. Both of these operations require heat, and, since it is taken from the heat of the mixture, a fall of temperature results. This process is used in freezing ice-cream.

When saltpeter is dissolved in water, the temperature of the latter falls several degrees. Many other mixtures and solutions give similar results. These are called *freezing mixtures* and are used in producing low temperatures. In all such cases the fall of temperature is due to the subtraction of heat from the mixture to supply the energy needed for liquefaction.

FIG. 213. Iron when melted can be poured like water

What is a freezing mixture? How may one be made? What use can be made of it? Why does a mixture of salt and ice cause a low temperature?

EXERCISES

1. Why are water faucets sometimes left running on cold winter nights?
2. Why do iron castings have sharp edges?
3. Why is it difficult to make snowballs in very cold weather?

4. Which would be better for a refrigerator, ten pounds of ice or ten pounds of water at 0° C.? State reasons.

5. It has been proposed by a commercial firm to decrease the expense of ice used in home refrigerators by wrapping the ice in a special blanket which they sell. Discuss this.

6. State the reason for the behavior of freezing mixtures.

7. Why cannot ice be used by itself in the making of ice cream? Is it just a question of time?

8. Make a diagram of a fire hydrant, showing how freezing is avoided.

9. Is snow as good as ice for a freezing-mixture? Explain.

10. Should ice be placed at the top or bottom of a refrigerator? Explain.

11. Why is it more difficult to skate when the temperature is much below the freezing-point?

12. A thin copper wire will cut through ice more quickly than a thick one (Fig. 212*b*). Explain.

13. Is the action of frost in the ground of any benefit to the farmer? Explain.

14. Large rocks are most apt to fall in the high Alps between midnight and dawn. Explain.

PROBLEMS

1. How much heat would be required to convert 1 kilogram of ice at 0° C. into water at the boiling point?

2. 500 g. of ice at 0° C. were placed in 500 g. of water at 10° C. what was the result?

3. A kilogram of ice at 0° C. and a kilogram of water at 0° C. were placed in a vessel in a room at 0° C. What was the final condition of the mixture?

CHAPTER XXVII

VAPORIZATION

247. Vaporization and Condensation.—The passage of a substance from the liquid to the gaseous state is called *vaporization.* It can take place in two somewhat different ways, and these we call *evaporation* and *boiling* (or ebullition). The reverse passage is called *condensation* (or liquefaction).

Define vaporization; condensation.

248. Evaporation.—This, *the invisible passage of a liquid into the gaseous state,* is a familiar phenomenon. Water, exposed in an open vessel, gradually disappears. Wet clothing, hung outdoors in fine weather, becomes dry. When a fountain pen is left without the cap on, the ink dries on the pen. Many liquids must be kept in stoppered bottles, or they will disappear.

What becomes of the liquid in such cases? A few drops of ether at the bottom of a flask will soon vanish, and a lighted match, applied to the mouth of the flask, will cause a flash, thus showing that the flask contained an inflammable vapor. (Use only a few drops and put the ether bottle away before lighting the match.)

Now what is happening when a liquid evaporates? As we learned earlier, many of the molecules of the liquid are moving with more than average speed. Some of these livelier molecules near the surface are able to jump out of the liquid, in spite of the force of cohesion that restrains the others. This leakage of the swifter molecules is what we call evaporation.

Define evaporation. Give illustrations of the process. Is it ever advantageous? Disadvantageous? What becomes of the liquid which evaporates? Explain the process of evaporation.

249. The Rate of Evaporation.—Clothes dry more quickly in sunshine and in a brisk wind. Vessels dry more quickly when heated. Ink on a freshly written page can be dried by waving the sheet in the air. Such illustrations show that evaporation is hastened by *heating* and by *air currents.*

The rate of evaporation also depends on *the area of the free surface.* Water evaporates more rapidly from a pan than from a jar. Ink wells are made with small openings to diminish evaporation.

What three factors influence the rate of evaporation? Give illustrations of effect of each.

250. Saturation. A liquid evaporates more quickly into a space that contains little of the vapor. Air currents promote evaporation by removing the vapor-laden air. A liquid that partly fills a closed vessel will evaporate until a certain amount of vapor is present, and then the amount of vapor will cease to increase. (Fig. 214.)

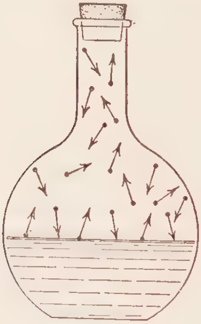


FIG. 214. Vapor Pressure

When the vapor in a closed space above a liquid does not increase, the space is said to be **saturated** with the vapor, and the vapor is called **saturated vapor.**

If the space over a liquid contains vapor of the liquid, what effect is produced on the rate of evaporation? Does evaporation go on indefinitely in a closed vessel partly filled with a liquid? Why? What is saturated vapor?

251. Vapor Pressure.—A vapor consists of flying molecules, and exerts pressure, just as air or any gas exerts pressure. The *pressure of saturated vapor* can be measured by introducing a drop of the liquid into the vacuum above the mercury in a barometer (Fig. 215). The pressure of the vapor will depress the mercury by an amount that can be measured. This is the pressure of the saturated vapor.

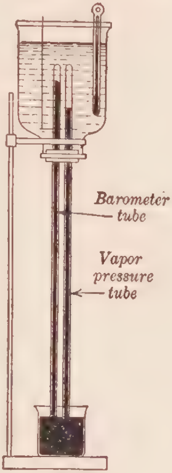


FIG. 215.

If the part of the tube occupied by the vapor be warmed, the depression of the mercury will increase. Hence *saturated vapor pressure is greater the higher the temperature.*

Why does a vapor exert pressure? How may its pressure be measured? How does temperature affect the pressure of saturated vapor?

252. Heat Required for Vaporization.—Heat is required for evaporation, and if it is not supplied by some source of heat, such as a flame, it will be taken from some body in contact with the evaporating liquid or from the liquid itself. Thus, when a drop of ether or gasoline on the hand evaporates, the hand is cooled. Fanning the face on a hot day cools the skin by promoting evaporation of the perspiration.

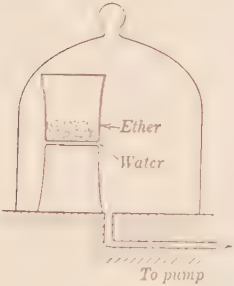


FIG. 216. Freezing Water by Rapid Evaporation of Ether

Wet the bottom of a small beaker and place it on another beaker which has been inverted. Pour a little ether in the upper beaker, place the beakers under the receiver of an air-pump and pump air and ether vapor from the jar (Fig. 216). The rapid evaporation of the ether will freeze the water between the beakers and bind them together.

Fill a very porous jar and a tumbler with water, and place them in the strong current of air in front of an electric fan.

Put a thermometer in each. The temperature of the water in the porous jar will soon fall below that of the water in the tumbler, owing to the evaporation of water that soaks through the pores of the jar. In hot climates drinking water is sometimes cooled in this way. (Fig. 217.)

Fig. 217. Spanish Water Jar

What is necessary in order that a liquid may be evaporated? What are some of the sources of the heat? Why does fanning your face on a hot day cool it? Describe an experiment to show cooling by evaporation. How is drinking water sometimes cooled in hot countries when ice is unavailable?

253. Heat of Vaporization.—The heat of vaporization of any substance is the amount of heat required to change one gram of the substance into vapor at its ordinary boiling point. This is also called latent heat of vaporization. The same amount of heat is given up by one gram of the vapor in condensing to a liquid.

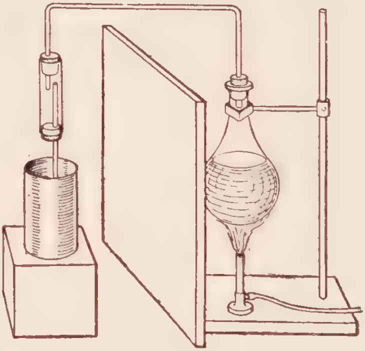


Fig. 218. Determining Heat of Vaporization of Water

The heat of vaporization of a liquid can be found by means of the method of mixtures. To find the heat of vaporization of water, a calorimeter is weighed, then partly filled with water, and weighed again. The temperature of the water is noted. Steam from a boiler is then run into the water (Fig. 218). When the temperature has risen about 20 degrees, the boiler is disconnected, the temperature of the water is noted, and the calorimeter with its contents is weighed again, in order to find the mass of steam condensed. When care is taken, the heat of vaporization of water is found to be 539, that is to say, it takes 539 calories to vaporize one gram of water at 100° C., but it is somewhat different at other temperatures.

Define heat of vaporization. Is the same amount of heat given up when a vapor condenses? How may the heat of vaporization be found? In the experiment, what are the sources of the heat? What becomes of it? What is the heat of vaporization of water?

Example. *A calorimeter, the mass of which is 100 grams and the specific heat 0.1, contains 300 grams of water at 20° C. It is raised to 50° C. by 15.7 grams of steam at 100° C. Calculate the heat of vaporization.*

The water equivalent of the calorimeter is 10.

To heat 310 g. of water 30° requires	9300 cal.
The water produced by condensation cools 50°, giving up 15.7 × 50 or	785 cal.
Therefore the heat given up by 15.7 g. of steam in condensing is	8515 cal.

Heat of vaporization = 8518/15.7 = 542 cal. per gm.

HEAT OF VAPORIZATION

Alcohol	205	Liquid Air	51
Ammonia	326	Mercury	65
Ether	90	Water	539

254. Refrigerating Machines.

—The cooling produced by the rapid evaporation of ammonia is used in machines for making ice and for operating cold storage plants. The ammonia is first condensed to a liquid in a coil of pipe (Fig. 219), by pressure and cooling. It is then allowed to pass into a second coil

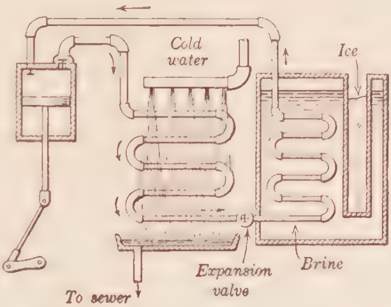


FIG. 219. Principle of Artificial Refrigeration

and there it boils under reduced pressure. The heat required is taken from brine that surrounds it, and the cooled brine is pumped into the refrigerating chamber. The ammonia gas is then condensed to a liquid by cooling and pressure, and the operations are repeated.

How is brine cooled for use in cold storage plants? What becomes of the heat taken from the brine? How may the ammonia be used over again? How is artificial ice made?

255. Distillation.—When a mixture of two or more liquids is heated, one liquid reaches its boiling point before the others. If the mixture of vapors formed be condensed in a second vessel, the liquid obtained will be chiefly the one of lowest boiling point.

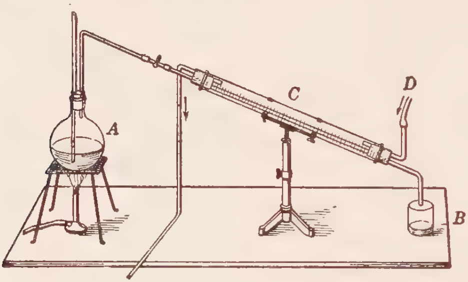


FIG. 220. Distillation

In this way alcohol can be separated from water and water can be freed from impurities. Gasoline, kerosene, and mineral lubricating oils are all obtained from petroleum by distillation (Fig. 220).

What is distillation? What two processes are involved? What is the process used for? How may two substances be thus separated?

256. Condensation.—The change of a vapor into a liquid is called *condensation.* It takes place in the formation of clouds, which consist of minute drops of water, and whenever a very cold body, such as a pitcher containing ice and water, is brought into a warm moist atmosphere. The steam from the cylinder of a steam engine is condensed by being forced into a tank of water. Any gas, no matter how permanent it may seem, may be liquefied by sufficient cold and pressure. In this way air and other gases are first liquefied and then solidified.

In a closed vessel that contains a liquid and a saturated vapor, evaporation and condensation are both continually taking place; but they proceed at equal rates, and the quantity of vapor remains constant.

Define condensation. How are clouds formed? Why do drops of water often form on the outside of a pitcher of ice water? How may the condensation or liquefaction of all gases be accomplished? What goes on in a closed vessel partly filled with a liquid?

257. Boiling or Ebullition.—When water is raised to about 100° C., it begins to boil. Bubbles of vapor are formed *in the liquid* and rise to the surface, where they burst and scatter their vapor into the atmosphere. While they are in the liquid the bubbles consist of saturated vapor. The pressure of this vapor must be as great as the atmospheric pressure, or the bubbles could not exist long enough to reach the surface. These facts give us a most important piece of information:

A liquid in an open vessel begins to boil when it reaches the temperature at which its saturated vapor pressure equals the atmospheric pressure.

What is the difference between evaporation and boiling? If a liquid is heated in a closed vessel, when does it begin to boil?

258. Boiling Under Different Pressures.—It follows from the last statement that, when the pressure above a liquid changes, its boiling point also changes. When a vessel containing warm water is placed under the receiver of an air-pump and subjected to diminished pressure, it boils below 100° C. If a round-bottomed flask, partly filled with water (Fig. 221), be brought to boiling, and be then stoppered and inverted, boiling will cease; but cold water poured on the flask will start the boiling again. The cold water cools and condenses some of the vapor in the flask, and boiling under diminished pressure takes place. The dependence of the boiling point on pressure explains why we state the atmospheric pressure in defining the boiling point on a thermometer (§207).

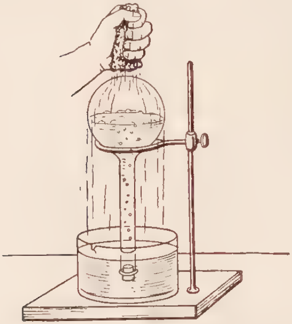


FIG. 221. Boiling under Diminished Pressure

The pressure of the air at the top of a mountain is less than at the foot of the mountain, and water boils at a lower temperature. On Pike's Peak water boils at 86° C. At such heights it takes a long while to cook an egg in boiling water. The fall of the boiling point is about one degree Centigrade for each 1080 feet of ascent.

In the manufacture of sugar from sugar cane the water must be removed; but, if the juice were raised to the ordinary boiling point of water, the sugar would be turned into invert sugar. Hence the water is boiled away under reduced pressure, at about 60° C., in "vacuum pans" (Fig. 222*a*).

When subjected to pressures greater than one atmosphere, water must be raised to temperatures above 100° C. before it will boil. At a pressure of about one atmosphere, the boiling point is raised 0.4° C. for each cm. of increase of pressure on the mercury gauge. The temperature of the steam in high pressure boilers is very high, and burns due to the bursting of steam pipes are very serious. The temperature of water boiling under a pressure of 150 lb. per sq. in. is 181° C., under 300 lb. per sq. in. it is 214° C., and under 500 lb. per sq. in. it is 241° C. Such pressures are not uncommon in the small boilers of steam automobiles. The intermittent ejection of water and steam by a geyser (Fig. 222*b*) is caused by some sudden decrease of pressure on water heated, deep down in the earth, to a temperature higher than the ordinary boiling-point.

What effect does a lessening of the pressure have on the boiling point? An increase of pressure? Why? Show how a liquid may be made to boil by lowering the pressure upon it. Is the air pressure the same at all altitudes? Does water boil at the same temperature on top of a mountain as at sea level? Why not? Why is it difficult to boil potatoes on a mountain top? Why is sugar syrup evaporated in vacuum pans? Why is the temperature in a steam boiler much above 100° C.? Is the boiling point of mercury high or low? Alcohol?

FIG. 222*a*. Sugar Vacuum Pan

FIG. 222*b*. Nature's boiling-pot. The Giant Geyser of the Yellowstone Park, 200 ft. high

BOILING POINTS
(at 76 cm. pressure)

Alcohol	78.2° C.	Mercury	357° C.
Ether	34.6 °C.	Water	100° C.

259. Sublimation.—Many solids can turn into vapor without passing through the liquid state. This is called *sublimation.* Thus, in cold climates, snow will slowly disappear, even when the temperature is constantly below the melting point. Camphor, iodine, and other substances sublime at ordinary temperatures.

Substances that can pass directly from the solid state into vapor can also pass back again into the solid state, without becoming liquids. Hoar frost is ice formed in this way from water vapor at low temperatures of the air. Camphor in a closed bottle is continually going through both processes.

What is sublimation? Why does snow slowly disappear even though the temperature is low? How is frost formed on a window pane?

260. Water Vapor in the Air.—Sometimes the atmosphere contains very little water vapor, and it is then described as *dry.* At other times it contains much, and is said to be *moist.* Winds, coming from places where rapid evaporation is taking place, bring moist air. Evaporation is most rapid where there are large bodies of water and where the temperature is high. Generally speaking, winds from oceans and large lakes are apt to be moist, while those from inland are more frequently dry.

What is the source of the water vapor in the air? Is it constant? Why do winds from the ocean often cause rain?

261. Dew Point.—The amount of water vapor in the air is usually much less than that which is required to saturate it. We have already seen that to saturate a space requires less vapor the lower the temperature is. Hence, if the air be steadily cooled, a temperature will ultimately be reached at which it will be saturated.

The temperature at which the amount of vapor actually in the air would saturate it is called the **dew point.** When the amount of vapor in the air is nearly enough to saturate it, as on a "muggy" day in summer, the dew point is only slightly below the temperature of the air. On a clear day in winter the vapor in the air is small, and the dew point is much below atmospheric temperature.

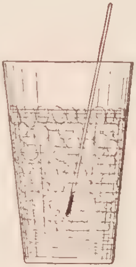


FIG. 223. Finding the Dew Point

To find the dew point, half fill a polished metal cup (a "soda shaker") with water, put a small lump of ice in it, and stir with a thermometer (Fig. 223). Note the temperature of the water when moisture begins to form on the outside of the cup. This is the dew point. In a dew-point **hygrometer** the cooling is obtained by the evaporation of ether.

What happens to the air when it is continuously cooled? Define dew point. Is it always the same temperature? Why not? How may the dew point be found?

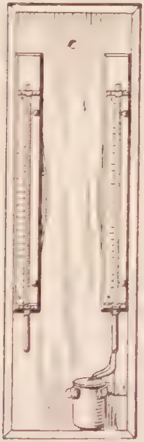


FIG. 224. Hygrometer

262. **Relative Humidity of the Air.**—When the atmosphere is nearly saturated with water vapor, we feel uncomfortable, because the moisture that issues from the sweat-glands, as part of the process of regulating the temperature of the body, does not then readily evaporate. From this point of view the **relative humidity**, which is **the ratio of the pressure of vapor in the air to the pressure that would saturate it,** is of greater interest than the *actual* amount of vapor in the air.

The relative humidity can be found from the readings of two thermometers, called respectively *the wet and dry bulb thermometers* (Fig. 224). The wet bulb thermometer is kept moist by a strip of muslin that dips in a small beaker of water. The other is an ordinary thermometer. Water continually evaporates from the wet bulb, at a rate that is greater the less the amount of vapor in the air, and the heat required is taken from the thermometer itself, which therefore is cooled. From the readings of the two thermometers and certain tables prepared by the Weather Bureau, the relative humidity, the vapor density, and the dew point can be found.

Why are we uncomfortable when the air is nearly saturated? What is the purpose of the sweat glands? Define relative humidity. How may it be found? Describe the operation of a wet bulb thermometer. What does a low reading of the wet bulb thermometer signify? What furnishes the heat which evaporates the moisture on the bulb?

263. Summary of the Effects of Heat on Water.—Water is such an important agent in nature, and its properties as regards heat are so exceptional, that we shall give a brief summary of them.

Freezing.—Unlike most substances,, water, when it freezes, becomes less dense. Hence the ice on the surface of a body of water in winter has no tendency to sink. The crust thus formed tends to protect the rest of the water from freezing. Thus a river can continue to flow beneath its solid covering of ice.

Heat of Fusion.—The heat of fusion of ice is exceptionally great. This prevents sudden freezing of an open body of water. The high heat of fusion of ice also hinders sudden melting of snow and ice in the springtime, and tends to prevent heavy floods. In cold climates driving and skating on the ice are possible for several months of the year. This would all have been very different if the heat of fusion of ice had been as small as that of mercury.

Expansion.—Water is remarkable in the property it has of contracting as it is heated from 0° C. to 4° C. A large proportion of the water in a large pond never cools below 4° C., since this is the lowest temperature at which it contracts and sinks when it is cooled. Thus living things in the water are protected during the cold of winter.

Specific Heat.—Because of its very great specific heat, water can receive or give up large quantities of heat without great changes of temperature. This accounts for the small fluctuations of atmospheric temperature near the sea, as compared with those common inland. In the southern hemisphere, where there is much more water than land, winters are not, in general, so cold, nor summers so hot, as in the same latitudes in the northern hemisphere.

Heat of Vaporization.—The great amount of heat required to vaporize water prevents too rapid formation of vapor in the air. Were it not for this, and the warming effect of the heat given up by water vapor as it condenses to form clouds and rain, downpours of rain would be much more frequent and destructive.

A review of the properties of water, its high heat of fusion and of vaporization, its high specific heat, its contraction on melting and its further contraction as its temperature is rising to 4° C., shows that it is an exceptional liquid. These peculiarities of water have very important effects on many natural phenomena.

Why do we give special attention to the heat properties of water? Why does ice float? What importance attaches to this? Is the heat of fusion of water large or small? How does this fact assist in preventing spring floods? In what other ways is it of importance? What peculiarity has water in regard to expansion with heat? At what temperature is it heaviest? Why doesn't a pond freeze clear to the bottom on a cold night? Of what importance is the large specific heat of water? Why do sea coasts have more moderate temperatures than inland places? Why are southern summers cooler and southern winters warmer than those in the northern hemisphere? What effect does the high heat of vaporization of water have on the amount of rainfall?

EXERCISES

1. Will clothes dry more quickly on a windy or a quiet day?

2. The glass of show windows is sometimes covered with moisture on the inside in winter. Why is this prevented by a current of air from an electric fan?

3. Burns by steam are much worse than burns by water at the same temperature as the steam. Why?

4. The steam which goes into a radiator is frequently of the same temperature as the water which leaves the radiator. How can a room be heated under these conditions?

5. Why is it dangerous to sit around in damp clothes?

6. Why is it important to avoid draughts of air, even if the air is warm, when you are overheated?

7. Why does a little gasoline, spilled on the hand on a cold day, seem much colder than water would at the same temperature?

8. In India drinking water is kept in a porous earthenware jar, which is hung in a draft of air, if possible. Why?

9. Why does it take such a comparatively long time to boil away a quart of water?

10. People who wear glasses, entering a restaurant on a very cold day, frequently find that their glasses cloud over. Explain.

11. Why is a metal ice pitcher containing ice water frequently covered with water on the outside?

12. What is the white cloud that comes in puffs from a non-condensing engine? Is it steam? What becomes of it?

13. What is the effect of pressure on the boiling point? Why should an effect be produced?

14. Water can be boiled on mountain tops at a temperature far below 100° C. Is this an advantage to the cook? Explain.

15. Mountain guides in Switzerland like to astonish their patrons by drinking tea when it is nearly boiling. Is this as remarkable as it seems to be?

16. On ships it is customary to use pressure boilers for cooking. Can you give a reasonable explanation of this?

17. Would it be safe to heat a can of beans in an oven and then apply the can opener?

18. How can clothes dry if hung out when the temperature is below freezing?

19. Why is it desirable, in steam heated apartments, to keep a pan of water on the radiator?

20. Explain why some hot days in summer are more comfortable than other days when the temperature is lower.

PROBLEMS

1. How many g. of steam would be required to melt 1 kilogram of ice at 0° C. and convert it into water at 24° C.? How much water at 100° C. would be required to do the same thing?

2. A kilogram of steam at 100° C. is blown into 20 kilograms of water at 20° C. What is the resulting temperature?

3. What amount of heat is required to transform 500 g. of ice into steam at 100° C.?

4. How much coal is required to transform 1000 kilograms of water at 20° C. into steam at 100° C., if 1 g. of coal in burning produces 7800 calories?

CHAPTER XXVIII

TRANSFER OF HEAT

264. Methods of Transfer.—Heat is transferred from one body to another in three ways. Hold one edge of a copper cent in the flame of a match. Heat will be *conducted* through the copper to the hand. Hold the hand some distance above the flame and it will be felt that heat is *carried by currents* of hot air. Then place the hand near one side of the flame and the heat *radiated* by the flame will be perceived. The three processes are illustrated in the older type of incandescent lamp, from the bulb of which the air is removed by an air-pump in the process of manufacture. Heat is radiated from the hot wire to the glass, passes through the glass, partly by conduction and partly by radiation, and is dispersed through the room by air currents.

In what three ways is heat transferred from one body to another? Give an example of each.

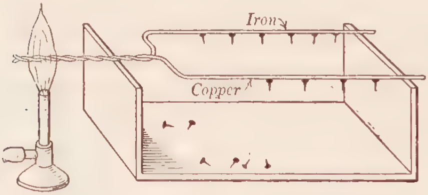


FIG. 225. Conduction of Heat by Metals

265. Good Conductors of Heat.—Substances differ widely in their conducting power. Metals are the best conductors. If one end of a nail of about the same size as a match be held in the flame of the match, the very different rates at which the iron and the wood conduct heat will be obvious.

But metals differ widely from one another in this respect.

A simple method to illustrate this is to twist the ends of two thick wires of copper and iron together (Fig. 225) and heat the twisted part in the flame. Nails attached to the wires by paraffin wax will show the superior conducting power of the copper by the greater distance to which the copper is hot enough to melt the wax and thus release the nails.

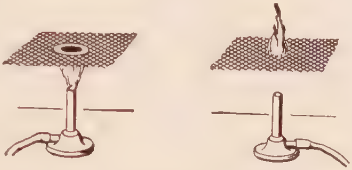


FIG. 226. Principle of Safety Lamp

The high conducting power of copper is well shown by the following experiment. Place a sheet of copper gauze of fine mesh over a Bunsen burner (Fig. 226). Ignite the gas either above or below the gauze; the flame will not pass through to the other side. The copper wire conducts the heat away from the flame so rapidly that the gas is cooled to a temperature below the ignition point. Davy's safety lamp (Fig. 227) for miners is an application of this principle.

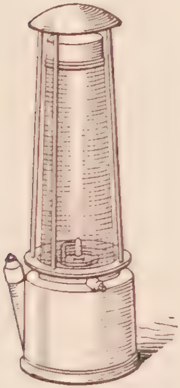


FIG. 227. A Davy Safety Lamp

The following metals are arranged in the order of their conducting powers: silver, copper, aluminum, zinc, brass, iron, bismuth. The first of these is about fifty times as good a conductor as the last.

Are all substances equally good conductors of heat? What class of substances conducts heat well? Describe an experiment to test the relative conducting powers of two or more metals. How is the conductivity of copper made use of in the Davy lamp? What metals are the best conductors?

266. Poor Conductors of Heat. — Many substances are useful because they are poor conductors. A pad of flannel is used to lift a hot pan or flatiron, and a wooden handle is put on a soldering iron, because flannel and wood are poor conductors. A fireless-cooker is a thick-walled box of very poor conducting material; food that has been brought to the proper temperature for cooking is placed in the box, and cooking proceeds for a long time without additional heating. Ice houses are sometimes made with double walls, between which sawdust is packed. A vacuum is a non-conductor. A vacuum bottle (so called "Thermos" bottle) is useful for keeping liquids hot or cold (Fig. 228).

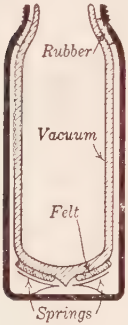


FIG. 228. Thermos Bottle

Glass is a poor conductor. Heated at one point it will expand, while it may be cool and unexpanded at neighboring points. Hence it is apt to crack if subjected to sudden changes of temperature. A cut-glass dish must not be plunged into hot water nor taken suddenly from a warm room to a cold one. Hot lamp chimneys break when a drop of cold water falls on them.

Mention several uses made of poor conductors of heat. Why is sawdust often placed between the walls of a refrigerator? Describe a fireless-cooker. Why is special care required in washing cut glass dishes?

267. Conductivity of Liquids and Gases.—That water is a poor conductor is shown by the experiment indicated in figure 229. Pieces of ice are kept, by a bit of wire, at the bottom of a test tube containing water. By heating the upper end of the tube, the water can be made to boil there, while the ice remains unmelted at the other end.

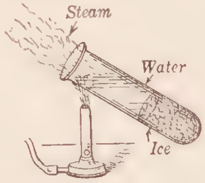


FIG. 229. Boiling Water over Ice

Air is also a poor conductor of heat. It is for this reason that an air space is left in the walls of houses and between a storm window and the inside window. This air serves as a blanket to keep the heat in the house from escaping in winter time. The warmth of woolen clothing is very largely due to the air enclosed between the fibers of the wool.

Is water a good conductor of heat? How can this be shown? Is air a good conductor or a poor conductor? Why is a woolen sweater so warm?

268. Convection in Liquids.—When matter is transferred from one place to another, the heat that it contains goes with it. This is called *convection* of heat. When a tea kettle is placed on the fire, convection at once begins. The lowest part of the liquid becomes heated by conduction through the bottom of the kettle, and rises to the top. The process is clearly shown when a glass flask that contains water and some sawdust is heated by a Bunsen burner (Fig. 230). The water *circulates*, rising in the middle of the vessel and sinking along the sides.

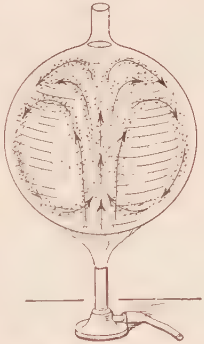


Fig. 230. Convection Currents in Water

Ocean currents, such as the Gulf Stream, which flow from the more highly heated parts of the ocean, carry immense quantities of heat with them to the colder regions.

When the surface of a pond or river is cooled in the winter, this colder water sinks and forces the warmer water to the surface. This process continues until the water at the surface cools to 4° C.; but the process then ceases, since, below this temperature, water, as we have seen, becomes less dense and therefore does not sink as its temperature is lowered.

Define convection. In what classes of substances is it effective? What causes the water in a tea kettle to circulate while it is being heated? How is heat transferred in large quantities from the equator to higher latitudes? Why does the water in a pond circulate when the pond is cooling? Why does this stop when the temperature reaches 4° C.?

269. Convection in Gases.—Gases are so light and mobile that they quickly show the effects of unequal heating (Fig. 231). The hot gases in a chimney rise, being forced up by the weight of the cooler and heavier air outside the chimney. When a strong draft is required, the chimney is made very tall, in order to increase the difference of pressure.

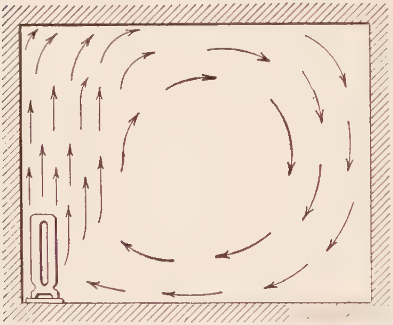


Fig. 231. Air Convection Currents in Room

The atmosphere exhibits convection and circulation on an immense scale. The heated air near the equator is continually rising and spreading outward toward the poles, while colder air flows inward along the surface of the earth. This gives rise to "trade winds" over the ocean near the equator, blowing from the northeast in the northern hemisphere and from the southeast in the southern. Near the sea or lake shore "sea breezes" occur. The air resting on the land is heated, expands, and overflows above, causing a decreased pressure over the land and an increased pressure over the water. As a result the air near the surface flows from the ocean toward the land. We call this a *sea*

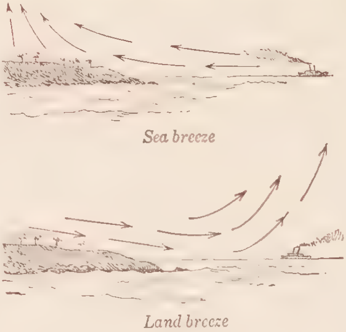


Fig. 232.

breeze. At night the conditions are reversed and a *land breeze* results. (Fig. 232.)

Why are gases particularly subject to convection? How does a chimney induce a draft through the fire? What effect has increasing the height of the chimney? Why? What is the principal cause of winds? Explain the sea breezes during the day. The land breezes at night.

270. Radiation.—Heat comes to us from the sun across millions of miles of space where there is no material in which conduction or convection can take place. The heat that we receive from an open fire is evidently not due to conduction or convection, since the air is drawn up the chimney. In such cases the heat is transmitted by *radiation,* and the heat so received is called *radiant heat.*

How do you know heat is not brought to us from the sun by convection? Is it brought by conduction? What is the process called? Define radiant heat.

271. Radiation Is a Wave Motion.—*Light* also comes to us from the sun and from an incandescent lamp. We shall see later that light consists of waves in a medium, called the ether, which exists everywhere in the universe. The light and the heat which come to us from a sufficiently hot body are essentially the same while they are on the way, and we speak of them as different only when we are thinking of the different effects they produce on the hand and on the eye.

It is, however, evident that radiant heat is not heat as we have already defined heat—namely, energy of motion of molecules—for this stream of wave energy in the ether can pass through matter without appreciably heating it. The hand is heated by sunshine coming in through a window, although the glass may feel cold to the touch. A block of ice placed in the sun melts on the under side as well as on top.

The radiant heat that passes through the upper air on its way to us from the sun does not heat the air much, as mountain climbers and those who have been to great heights in balloons and airplanes know.

We have already become familiar with the idea that one form of energy can be transformed into another. What was heat energy before it left a hot body becomes energy of wave motion in space, and returns to the form of heat energy when it falls on some body through which it does not readily pass. For this reason radiant heat is more properly called *radiant energy* or *radiation.*

What else comes to us from the sun by radiation? What is the nature of the process? How do we distinguish light from heat? Is radiant heat molecular energy? Is a substance heated by radiant heat passing through it? Give examples to prove this. What is necessary in order that radiant heat shall raise the temperature of a substance? What is the better term for radiant heat?

272. Good Radiators and Poor Radiators.—Substances differ as to the amount of heat they radiate when at the same temperature. This is well shown by the apparatus of figure 233*a*. *A* and *B* are two test tubes which are joined by a U-shaped glass tube containing a colored liquid. Exactly midway between the test-tubes is a metal vessel *C*, polished on the side toward *A* and lampblacked on the side toward *B*. If hot water be poured into this vessel, *B* will receive more heat than *A*, and the air in *B* will be more heated than that in *A*, as will be indicated by the motion of the liquid in the tube. Such experiments show that **dark surfaces are better radiators than bright ones.** The nickel-plated or aluminum sides of a tea kettle are an advantage in decreasing the radiation of heat from the water within,

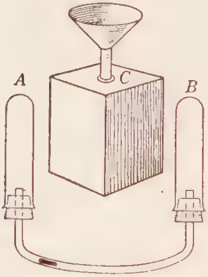


FIG. 233*a*. Good and Poor Radiators

and the blackened bottom an advantage in absorbing heat from the fire.

Rate of radiation depends on the extent of the surface of the hot body. For this reason rough bodies are, in general, better radiators than smooth ones. The radiators for heating a house are rough and in many small sections so that they may give off heat more rapidly. This is also the purpose of using many small tubes for the radiators of gasoline engines.

Do all surfaces at the same temperature radiate heat equally well? How may this be shown? Which are better radiators, bright surfaces or dark ones? Why are steam radiators for heating a house not polished? Why are they made in many small sections?

273. Absorption. Surfaces also differ in their capacity for absorbing radiation. This can be shown by a modification of the apparatus of figure 233*a*. Let *A* be a lampblacked test-tube and *C* a vessel polished on both faces. On pouring hot water into *C* it will be found that *A* absorbs more of the heat that falls on it than *B* does. (Fig. 233*b*.)

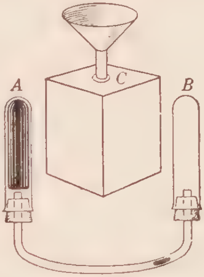


Fig. 233*b*. Good and Poor Absorbers

A thermometer with a lampblacked bulb warms up more quickly than a similar one with a clean bulb, if both are placed in sunshine or near a hot body.

If a piece of ice be wrapped in a black cloth, and another piece of the same size be wrapped in a white cloth, and both be placed on a board in bright sunshine, the former will disappear first. Snow covered with soot melts faster than clean snow. In hot climates white clothing is better than black, because it absorbs less of the sun's heat. It is also better in cold climates, since it helps to prevent the escape of heat from the body.

These are all illustrations of the principle that **good radiators are also good absorbers.**

The different absorbing qualities of dark and bright surfaces are well illustrated by the radiometer (Fig. 234). It consists of a very light aluminum wheel that carries four vanes. Each vane has a blackened face and a bright face. The wheel is mounted in a bulb from which most of the air has been removed by an air-pump. When the radiometer is placed in sunshine or near a hot metal ball, a black face absorbs more heat and becomes hotter than a bright face. Thus the air in contact with the black face is more heated and has a higher pressure than the air in contact with the bright face. The result is that the wheel rotates, because the push of the air against a black face is greater than that against a bright face.

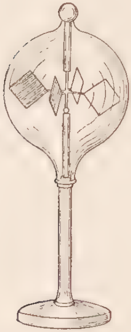


FIG. 234. Radiometer

Do all surfaces absorb heat at the same rate? How could you prove this? Which will get hot more quickly in the sunshine, a black rock or a light one? Why is white clothing worn in tropical regions? In general what relation exists between radiators and absorbers?

274. Transmission of Radiant Energy.—Window glass allows a large part of the radiant energy from the sun to pass through it, while wood and brick absorb it. Bodies that transmit radiant energy are said to be *diathermous.* Bodies which are opaque to radiant energy are described as *athermous.*

These terms must, however, be used with care. If a pane of glass be held before a gas flame or a hot fire, it will transmit only a little of the heat and will become very hot, owing to the heat that it has absorbed. Many bodies are, like glass, diathermous as regards radiant energy from bodies at very high temperatures, such as the sun, while athermous to that from a source at a comparatively low temperature.

The sun's heat passes readily through the glass cover of a hot-bed, but the heat radiated from the bodies within does not escape through the glass. Thus the heat within the enclosure increases until the accumulation is checked by the escape of heated air. Heat from the sun comes in through the atmosphere without heating it and heats the earth, but the heat radiated by the earth's surface is mostly absorbed by the atmosphere.

Define a diathermous substance. An athermous substance. Why does glass allow the sun's heat to enter a room but prevent the escape of the heat from a steam radiator? Why is a hot-bed effective in keeping early plants warm? Why does the atmosphere allow heat to reach us from the sun? What is the effect of the atmosphere at night?

275. Heating and Ventilation.—The need of heat in cold weather is familiar to all, but it is not so generally known that each of us needs at least 1500 cu. ft. of pure air per hour. Happily the means used for heating usually promote ventilation. The old-fashioned *fire-place* heats the walls of the room by direct radiation, and these heat the air by contact and convection. The draft of the chimney draws fresh air into the room and carries the impure air away. *Stoves* act partly by radiation but mostly by convection. They are more economical of fuel, since less heat escapes by the chimney, but a closed stove in a tightly closed room may be dangerous, owing to some escape of the products of combustion into the room.

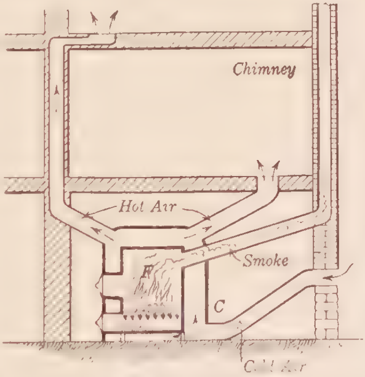


Fig. 235. Hot Air Heating System

A *hot air furnace* (Fig. 235) is a form of enclosed stove, from which heated air rises through pipes into the house and finally escapes through crevices at windows or doors, while fresh air is drawn in through an air duct. (Air from the cellar is apt to be contaminated.) This provides for ventilation. The heated air is usually very dry. A pan of water often forms part of the furnace, in order to moisten the air, but it is usually insufficient for the purpose.

In *hot-water heating* the heated water rises from the top of a boiler, and, after circulating through the radiators, returns to the bottom of the boiler. To allow for changes in the quantity and volume of the water, an "expansion tank" is provided at the top of the system (Fig. 236). The temperature of the water can be regulated through a wide range, according to the weather. The "radiators" radiate very little heat; the air is heated chiefly by contact and convection.

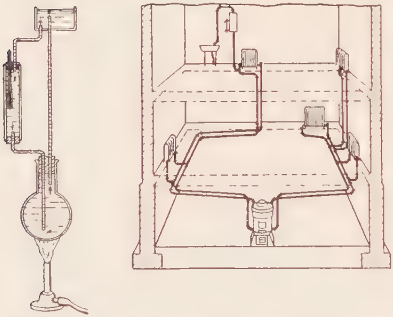


FIG. 236. Hot Water Heating System

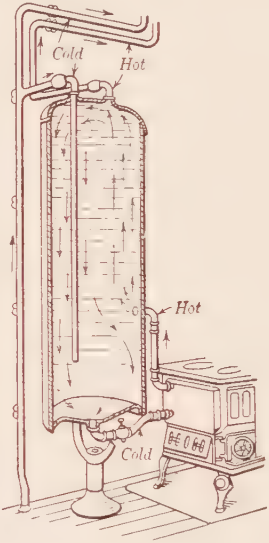


FIG. 237. Hot Water Heater

Gas-heaters for kitchen boilers and heating pipes in kitchen stoves take cold water in from the bottom of the boiler, and the heated water rises to the top of the boiler (Fig. 237). The cylinders of gas engines for automobiles and airplanes are kept cool by the circulation of water, which carries the heat to a radiator consisting of a large number of fine pipes.

In *steam-heating* (Fig. 238) steam formed in a boiler, rises, and is condensed in the radiators, and the water formed returns to the boiler. Because of the high heat of vaporization of water, the radiators do not need to be so large as in hot-water heating, but gentle heating for moderate weather is more difficult.

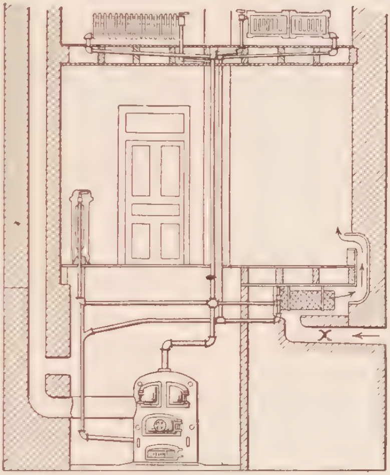


Fig. 238. Steam Heating System

How much pure air is needed for each person in a room? How does a fireplace act as a ventilator? A stove? Why is a stove sometimes dangerous? How does a hot air furnace supply fresh air to a house? Explain the process of convection in a hot water heating plant. How is the room heated from the radiator? Why is the radiator of an automobile made of many small pipes? How is the heat of steam made available for heating a room?

EXERCISES

1. What is the method of heat transfer in solids? Give several practical applications of the process.

2. Explain the process of convection, and give several practical applications of the process.

3. What is meant by heat radiation? How does it take place?

4. Just how is heat transferred from steam in a radiator to the room?

5. Explain in detail how the water in a metal vessel over a gas flame is finally raised to the boiling point.

6. Explain in detail how an icebox keeps food cold.

7. Describe the construction of a fireless cooker. Could it be used to freeze ice-cream?

8. How warm must air be before it starts to rise?

9. Heat may be transferred across a vacuum. Why do they use a vacuum in a Thermos bottle?

10. Can a metal Thermos bottle be as efficient as a glass one?

11. Why is the handle of a metal coffee pot frequently made of wood?

12. Why are the tubes of an automobile radiator made as small as possible and preferably of copper?

13. Why is a soldering iron made of copper?

14. Why is a flatiron made of iron rather than of copper?

15. Why are wash boilers made with copper bottoms?

16. On a cold morning why does oilcloth feel colder to the feet than carpet?

17. Why is the icebox of a refrigerator placed at the top?

18. It is possible to boil water in a thin paper disk without burning the paper. Explain.

19. There is an ice-cream freezer on the market that has a heavy glass cream-holder and a galvanized iron container. Is the design good?

20. If you want a sweater to keep you as warm as possible, should you wear it outside or inside your jacket? Explain.

21. Give three reasons why it takes a long spell of cold weather to form ice thick enough to skate on.

22. Is it better to build the back of a fireplace (open grate) of brick or polished tile?

23. Why is the handle of an iron stove lifter frequently surrounded by a heavy coiled wire?

24. From the physical standpoint, what is the best color for steam or hot water radiators?

25. Why are steam pipes frequently covered with felt or magnesia?

CHAPTER XXIX

HEAT AND WORK

276. The Steam Engine.—James Watt (1736-1819), a Scotch instrument maker in the University of Glasgow, was the inventor of the modern steam engine. Engines of a crude form had previously been used in pumping water from mines. Steam was admitted to the upper end of a vertical cylinder, in which there was a piston connected to the pump. The steam was then condensed by jets of cold water, so that a vacuum was produced above the piston, which was then raised by atmospheric pressure. To avoid the great waste of energy in heating and cooling the cylinder, Watt invented the **separate condenser** for the steam, "so that the cylinder should always be as hot as the steam that entered it" (Fig. 239). He also made the engine **double acting**, that is, each end was alternately connected to the boiler and to the condenser, so that the steam pressure pushed the piston first up and then down. These inventions changed the atmospheric engine into the steam engine, which

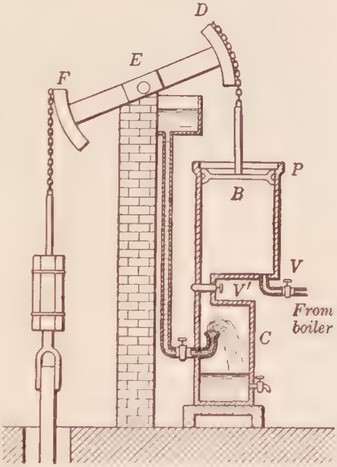


Fig. 239. Watt's Engine

has made steamships and railroads possible, and has played a most important part in the development of modern industry.

Who invented the modern steam engine? How did the early pumping engines work? Why were they really atmospheric engines rather than steam engines? What two principal improvements did Watt make?

277. Power Plants.—There are three essential divisions in a modern power plant, a **boiler** in which steam is generated, an **engine** where the heat energy of the steam is converted into energy of motion, and a **condenser** to take care of the waste steam. We shall not attempt to do more than to give the principles of their operation. If you will take the trouble to examine a "donkey-engine," a simple form of engine often used as a hoisting engine in erecting buildings, you will be better able to understand what follows.

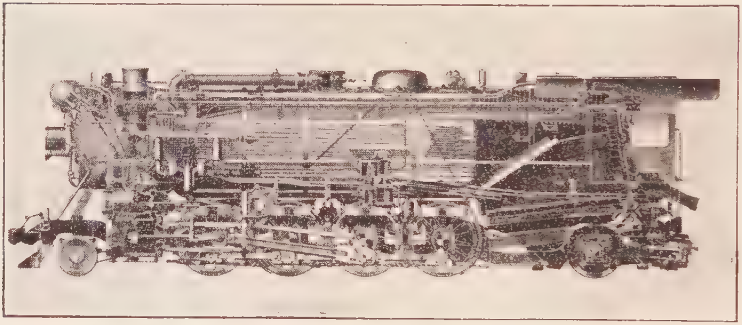


FIG. 240. Fire Tube Boiler in a Locomotive

Name the three main divisions of a power plant. What is the purpose of each?

278. Steam Boilers.—To increase the surface of water exposed to the heat of the flame, and so enable steam to be generated faster, *tubular boilers* are generally used. These are of two kinds. In *fire-tube boilers* the boiler consists of a cylinder in which tubes are set (Fig. 240). The water surrounds these tubes, and the flames and hot gases play through them. Locomotive boilers are of this type. In *water-tube boilers* the water is in the tube, and the flames on the outside (Fig. 241).

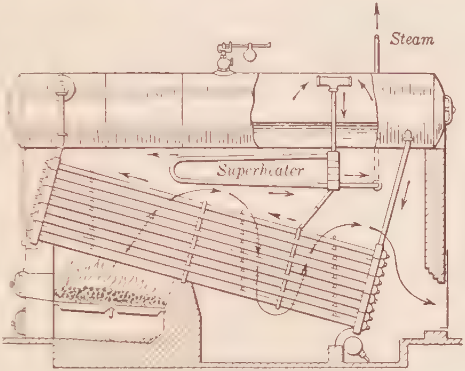


Fig. 241. Water Tube Boiler

To enable an engineer to know what steam pressure he is carrying in the boiler, a *steam gauge* is provided. This is a Bourdon tube, and its action has already been explained (Fig. 242). As the water in the boiler changes to steam, the water level is lowered. A gauge glass (Fig. 243) shows this level, and more water is forced in by means of a pump, when necessary.

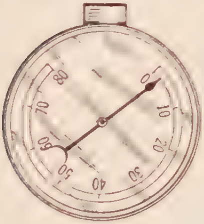


Fig. 242. Steam Gauge

An excessive pressure of steam might cause the boiler to explode. To avoid this danger, a *safety valve* is provided. This is a valve that is normally kept closed by a weight hung on a lever (Fig. 244). If the steam pressure becomes excessive, the pressure lifts the weight, and the valve opens, allowing steam to escape. By changing the position of the weight, such a valve can be set to open at any desired pressure.

Theoretically 1 lb. of coal should give about 14,400 B.T.U.'s, and should, starting with water at 212° F., evaporate 14.4 lbs.

of water, giving 14.4 lbs. of steam at 212° F. Actually the efficiency of a boiler is about 60 per cent. of this, for much heat is lost in the hot gases that escape up the chimney (flue gases), some coal is not completely burned, and there are various other heat losses from the boiler.

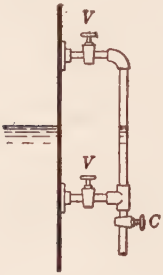


FIG. 243. Gauge Glass

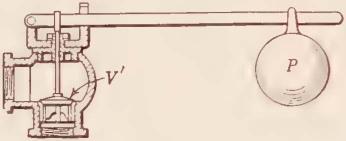


FIG. 244. Safety Valve

Why are boilers made with tubes rather than in one large tank? Distinguish between fire-tube and water-tube boilers. What is the purpose of a steam gauge? How is it made? What is a safety valve? Why is it necessary? How is it made? How is a safety valve set to open at a desired pressure? What is the theoretical heat value of a pound of coal? How much water should this evaporate at 212° F.? Does the boiler really evaporate so much? Why not? What is the efficiency of the boiler? Mention several sources of loss in operating the boiler.

279. Steam Engine.—A simple ideal engine is shown in figure 245. The steam from the boiler is led through the pipe *B* into the steam chest *C*. The steam chest contains a valve *D* that slides from one end of the box to the other, thus uncovering *ports* or passages that allow steam to pass either to the right or left hand side of the piston *E* that slides in the cylinder *F*. When this valve is in the position shown, steam is being admitted to the right hand end of the cylinder, thus driving the piston to the left. The steam in the other end of the cylinder, left there from the previous stroke, passes out through the exhaust pipe *G* to the condenser, where it is changed back to water, thus creating a partial vacuum on the exhaust side of the piston, and so aiding the steam to push the piston to the left. As the piston moves to the left, the valve is gradually closed by means of the eccentric rod *H*, until, when the piston has reached the left hand end of the cylinder, the passage *K* has closed and the passage *L* is open, thus admitting steam to the left hand end of the cylinder, and forcing the piston to the right.

This back-and-forth motion of the piston is changed by the crankshaft *M* to a rotary motion (also Watt's device). A pulley at the end of the shaft allows, by means of a belt, the energy of rotation to be used to drive various machines. To steady the motion of the crankshaft, a heavy flywheel *N* is fitted on it. When the engine starts, the setting in motion of this flywheel absorbs a large amount of energy, but after the engine has come up to speed, the flywheel acts as a control, equalizing the energy delivered at different parts of the stroke.

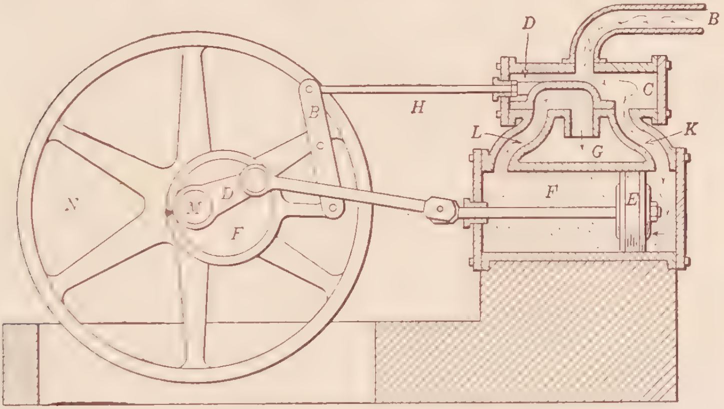


FIG. 245. Simple Ideal Engine

Such a simple engine may also be run *non-condensing*, that is, the exhaust steam may pass directly into the air, but this lowers the efficiency.

To keep the speed of the engine constant, a *governor* is used. One form, due to Watt, is shown in figure 246. The movable balls W, W' are connected to a sliding collar, which controls a valve that admits more or less steam to the cylinder. If the engine slows down, the balls drop, and the valve admits more steam, thus increasing the speed of the engine. If the engine runs too fast, as, for example, when a belt breaks and removes the load, the balls rise, and the valve cuts off the supply of steam.

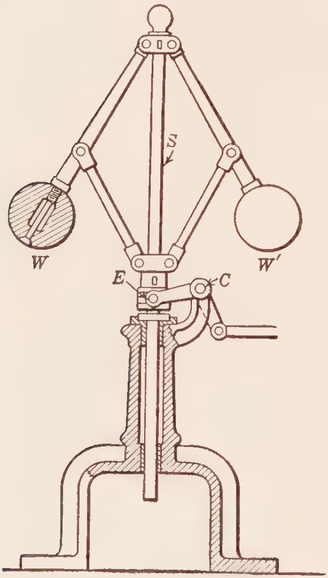


FIG. 246. Watt's Steam Governor

In figure 245 point out the steam pipe, the steam chest, the intake valve, the ports, the piston, the exhaust valve and explain the function of each. Why is a condenser added to the engine? How are the valves operated? How is the reciprocating motion changed to a rotary motion? Why is a flywheel necessary? What is a non-condensing engine? What is a governor of a steam engine? Describe one form. Explain it.

280. Compound Engines.—After steam has passed through the cylinder of such an engine as we have described, it still has a considerable amount of energy, and, when the steam is condensed, this energy is wasted in heating the condenser water. To avoid this loss, there are engines in which the steam, after having done its work in the first cylinder, passes into a second, larger cylinder, and is used over again. From this it is sometimes used in a third or even a fourth cylinder. Such engines are *compound, triple,* or *quadruple expansion* engines. Marine engines are often of this type.

What is a compound engine? A triple expansion engine?

281. Efficiency of a Steam Plant.—It can be shown that the efficiency of any engine could not be greater than $(T_1 - T_2)/T_1$ where T_1 is the absolute temperature of the entering steam and T_2 the absolute temperature of the exhaust steam. If the entering steam is at 180° C. and the exhaust steam at 100° C., then $T_1 = 453$ and $T_2 = 373$; the theoretical efficiency would then be $(453 - 373)/453 = 17.9$ per cent. The actual efficiency of such an engine is only about $3/4$ of this. If we combine this with the low efficiency of the boiler, about 60 per cent., you will see that the steam engine, although a very useful machine, is a very wasteful one.

What is the theoretical maximum efficiency of a steam engine? What is the approximate actual efficiency? Is a steam power plant an economical means of obtaining energy?

282. Steam Turbines.—In the engines that we have been considering, the piston reverses its direction at the end of each stroke. This sudden stopping and starting of a heavy mass of steel requires a heavy foundation for the engine, and causes a constant jarring of the building or ship, in which the engine is installed. These disadvantages are overcome in the *turbine*, which gives a direct rotary motion.

One common form, **Parson's turbine**, is something like an ordinary windmill, driven by steam instead of air (Fig. 247*a*). Inside of a cylinder there is a rotating drum with rows of curved blades fastened on its circumference. These are at such an angle that the steam, passing through the annular space between the drum (rotor) and the outside cylinder, pushes against the blades and causes the rotor to move. Stationary guide blades, attached to the outer cylinder, direct the steam against the moving blades (Fig. 247*b*). In moving

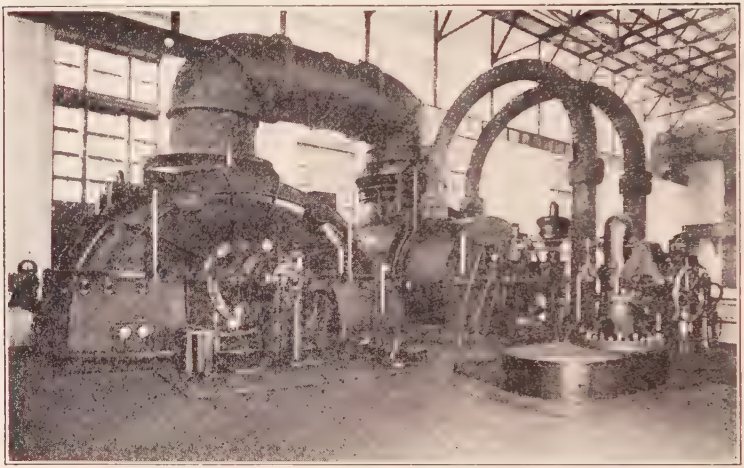


Fig. 247*a*. The Huge 107,000 horse power No. 4 Unit at the Hudson Ave. Generating Station of the Brooklyn Edison Company. This is the largest single unit in operation in the United States

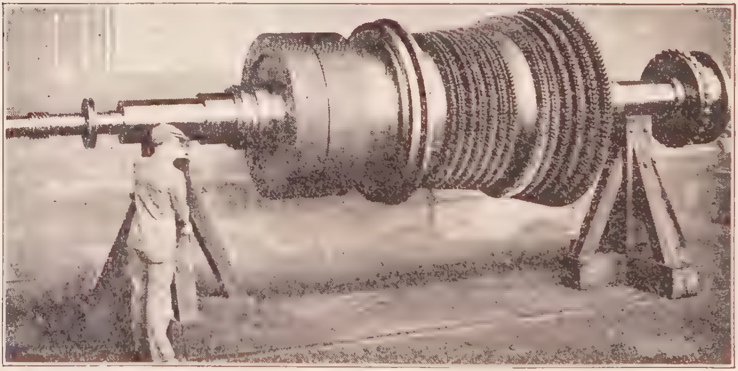


Fig. 247*b*. High Pressure Turbine Spindle
80,000 k.w. Turbine Generator Unit Installed in the Brooklyn Edison Co., Hudson Ave. Station

through the cylinder, the steam passes a row of fixed blades, which give it direction, then a row of moving blades, then another row of fixed blades, etc. (Fig. 247*c*.) In this process the steam expands, and it is necessary to make the blades longer as the outlet is approached and also to increase the diameter of the rotor.

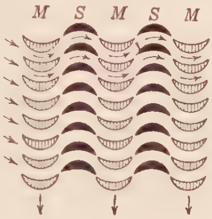


Fig. 247*c*.

Such a turbine is a beautiful example of accurate fitting. It contains many thousands of blades that must almost, but not quite, touch, and the rotor, weighing many tons, must be mounted so that it rotates smoothly.

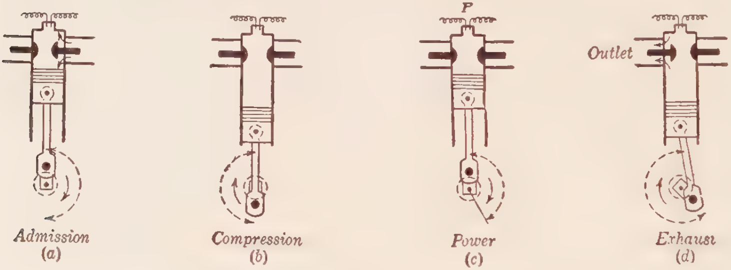
A good condensing system is essential for a turbine of high efficiency. This requires a high vacuum (sometimes a pressure of less than one inch of mercury) and large amounts of cooling water. Under the best operating conditions for each, turbines are somewhat more efficient than reciprocating engines.

What is the objection to a reciprocating engine? What is a turbine engine? Describe the Parson's turbine. Why are there two sets of blades? Why do the blades get longer nearer the outlet? Why does a turbine run so quietly? Which are more efficient, reciprocating or turbine engines?

283. Gas Engines.—In a gas engine the fuel is burned in the cylinder, and the explosive combustion produces the expansive force that acts on the piston. An explosive mixture of vapor and air is obtained by drawing air past a jet of gasoline in the *carburetor*. This mixture passes into the cylinder, where it is exploded and exerts force on the piston. Such engines are also called *internal combustion* engines, because the fuel is burned in the cylinder. Since the cylinder acts as a furnace, it is necessary to cool it either by water-jacketing or by a blast of cool air.

Why is a gas engine called an internal combustion engine? What is the purpose of the carburetor? Why does the cylinder of a gas engine get so hot? How is it cooled?

284. Four Stroke Engines.—An ideal gas engine cylinder is shown in figure 248*a*. In *a* the inlet valve is open, and, as the piston moves down, the explosive mixture of gasoline and air is being drawn into the cylinder. This is the *admission stroke.* In *b* the piston has reached its lowest point, and has started to move up. The inlet valve has closed, and the gas mixture is being compressed. This is the *compression stroke.* In *c* the piston has reached its highest position, and the gas is fully compressed. The passage of a spark between the two points of the spark plug *P* ignites the charge, and the piston is pushed down. This is the *power stroke.* In *d* the piston is again moving up. The exhaust valve is open, and the burnt gases are being forced out of the cylinder. This is the *exhaust stroke.* The engine is then in its original condition and ready to repeat the operations. As power is developed in only one out of the four strokes, the motion of such an engine would be very irregular. To steady it, a heavy flywheel is used. In automobiles we have not one, but four, six, eight, or even twelve cylinders to obtain a smoothly running car. A modern automobile engine is shown in figure 248*b*.



Admission (*a*) Compression (*b*) Power (*c*) Exhaust (*d*)

FIG. 248*a*. Principle of Gas Engine

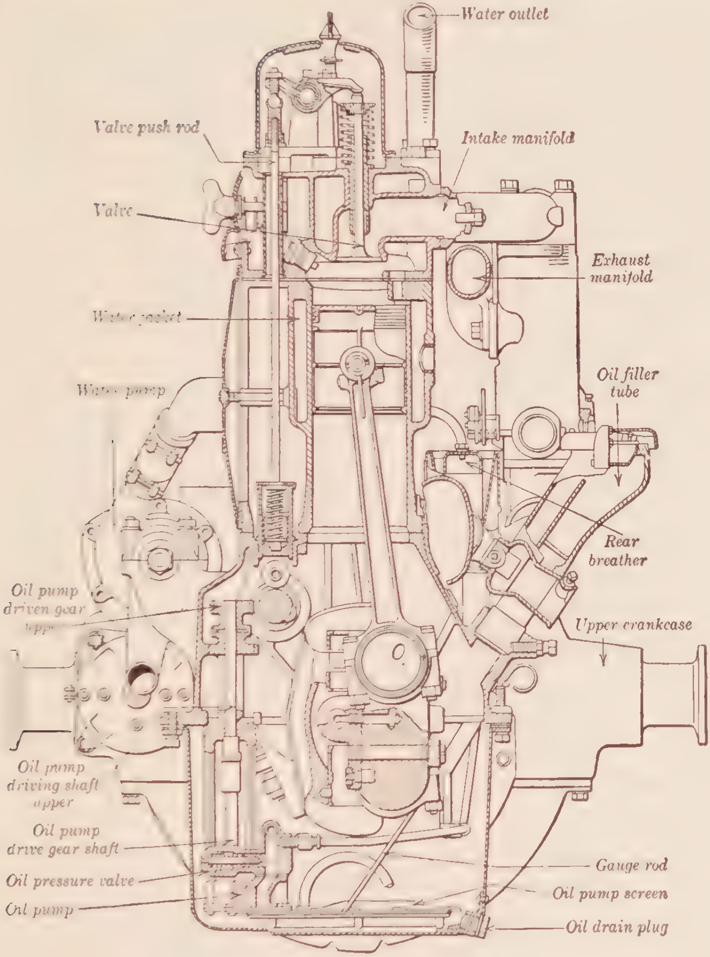


FIG. 248*b*. Buick Engine

What happens in a four cycle gas engine during the first down stroke of the piston? When it reaches the bottom? On its way up? When it reaches the top? During the next down stroke? During the following up stroke? How often is power supplied to the shaft? How is this irregular delivery of power overcome? Define: admission stroke, compression stroke, power stroke, exhaust stroke.

285. The Diesel Engine.—Compressing a gas develops heat. If we repeat the four operations of an ordinary gas engine, but *without using any gasoline,* and at the same time increase the compression pressure to several hundred pounds per square inch, the air will become hot enough to burn gasoline, without the aid of an electric spark. If, then, we squirt a few drops of gasoline into the cylinder at the instant when the air is most compressed, the gasoline will explode, and the engine will run as usual. This is the principle of the *Diesel engine.* A very heavy, slow-running engine, giving a very high compression, is used. Air is compressed, and then fuel oil is squirted into the cylinder. It burns, and the engine runs. Such engines are used because they burn a cheap oil and require little attention, compared with a steam engine of the same power.

What effect does compressing a gas have on its temperature? How is this effect utilized in a Diesel engine? What advantages has a Diesel engine over a steam engine or an ordinary gas engine?

286. Airplane Engines.—The older airplane engines did not differ much from those already described. The Wright engine (Fig. 248*c*), which has been used so successfully in flights across the Atlantic and Pacific, has its nine cylinders in one plane. The connecting-rod of the vertical or "master" cylinder acts directly on the crankshaft, and those of the other cylinders are connected to the crankshaft end of the connecting rod of the master cylinder by linkpins. There are three carburetors, each serving three cylinders, and two magnetos with two spark-plugs in each cylinder. The engine is air-cooled.

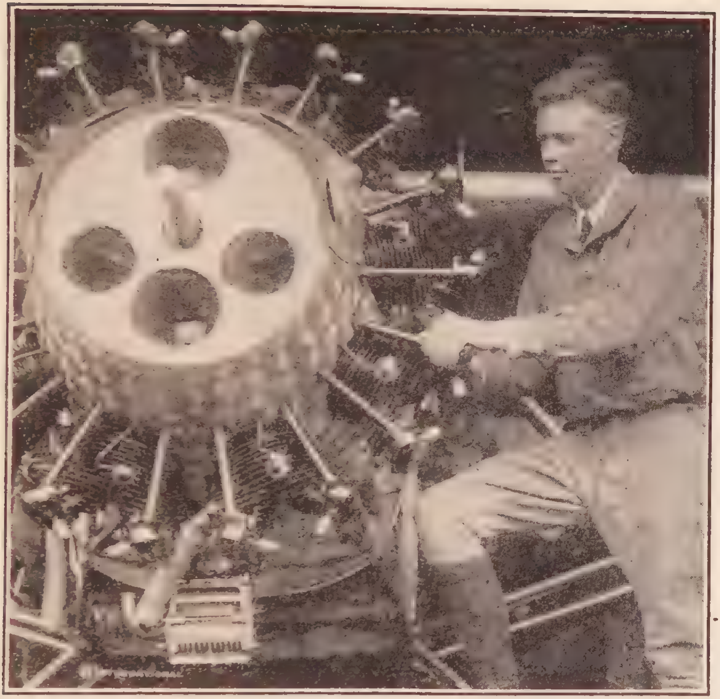


FIG. 248c. This Wright airplane engine was used by Colonel Lindbergh in crossing the Atlantic in 1927

287. Wasted Energy.—If you will think over all the machines with which you are familiar, you will realize that in all of them energy is wasted, largely because of friction, and this wasted energy goes into the form of heat. The bearings of a wheel become hot; two sticks rubbed together may produce enough heat to ignite them; iron struck by a hammer becomes too hot to hold. Such examples could be multiplied indefinitely. Since, in these cases, energy has been used up in increasing the temperature of these bodies, and since an increase in temperature means an increase in molecular kinetic energy, it is reasonable to suppose that there is a definite relationship between the amount of energy wasted and the amount of heat produced. James Prescott Joule (1818-89) proved this by an elaborate series of experiments.

Fig. 249*a*. James Prescott Joule (1818-1889) English physicist, whose accurate measurements laid the foundation of the Conservation of Energy.

What is the principal cause of wasted energy in machines? What becomes of this energy? Why do we believe that mechanical energy and heat energy are related?

288. Mechanical Equivalent of Heat.—To prove that the conversion of a definite amount of mechanical energy into heat always gave a definite number of calories, and to determine what this number was, Joule used the apparatus shown in Fig. 249*b*. It consists of a vessel *V* containing water, in which a series of paddles *P* could be rotated by the falling of the weight *W*. From the weight *W* and the distance *s* that it falls, the number of foot-pounds of work can be found; and from the temperature of the water at start and finish, as well as its mass, the number of calories gained can be found. Using all possible precautions to prevent the water gaining any heat except through the rotation of the paddles, and eliminating friction so far as possible, Joule found that 778 ft. lbs. of work, converted into heat, gave 1 B.T.U. This is equivalent to 427 Kilogram meters (4.19×10^7 ergs) for a calorie.

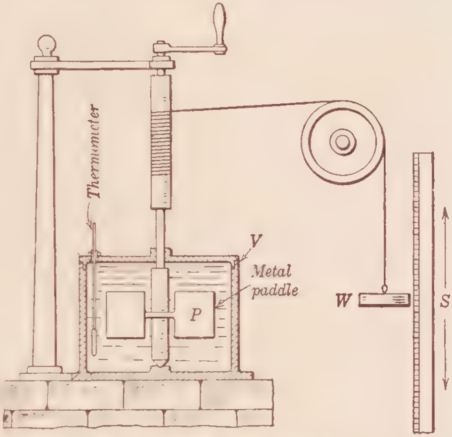


FIG. 249*b*. Joule's Experiment for Determining the Mechanical Equivalent of Heat

Describe Joule's apparatus for determining the relation between mechanical energy and heat. What was the source of the mechanical energy? How was the mechanical energy measured? How was it converted into heat? How was the heat measured? Define mechanical equivalent of heat. What is its value? Mention other experiments along this same line.

EXERCISES

1. Why are condensers always used on marine engines?

2. Why are condensers not used on most locomotives?

3. Would you provide for a condenser in designing a steam automobile?

4. An ordinary steam locomotive has an efficiency of only about 6 or 7%. What becomes of the rest of the energy?

5. Why are gears necessary in a gasoline automobile?

6. If the average pressure of steam in the cylinder of an engine is 100 lb. per sq. in. and the area of the piston is 40 sq. in., what amount of work is done by the steam in each 20 in. stroke of the piston?

7. What is the greatest possible efficiency of a steam engine the boiler of which is at 180° C. and and the condenser at 30° C.?

CHAPTER XXX

LIGHT

Sources and Transmission

289. Sources of Light.—Light is a form of energy to which the eye is especially sensitive and by means of which things are seen. Some bodies are *sources of light*, but most bodies are seen by light that they merely reflect. The sun and the stars are sources of light, but the light of the moon and the planets is reflected sunlight.

Most artificial sources of light are *solids at high temperatures,* such as the carbon and tungsten of electric lamps. Liquids also give off light when they can be raised to sufficiently high temperatures, for example the molten iron used in casting. Burning gases, such as hydrogen, are not luminous. The light of a burning gas jet or an oil lamp comes from carbon particles in the flame; a cold plate passed through it is blackened by soot or finely divided carbon that is cooled by the plate and deposited on it. The Bunsen flame contains few carbon particles and is only slightly luminous, but when a strip of asbestos is soaked in salt (sodium chloride) solution and wrapped around the top of a Bunsen burner, a bright yellow light is emitted by the sodium vapor in the flame. This "sodium light" is useful in many experiments. *Gases at ordinary temperatures* can be made luminous by passing a current of electricity through them, as in the mercury vapor lamp.

It would be more economical if light could be obtained without producing heat, for the heat is usually wasted. The firefly, luminous paint, and some kinds of decaying wood produce light without much heat, but we have not yet learned how to imitate this process.

What is light? How are most bodies made visible to us? What is the source of most of our artificial light? Do burning gases give light? How is a gas flame made luminous? How may a gas itself be made luminous? Is it possible for us to obtain light without heat?

290. Light Travels in Straight Lines.—To get to an object seen at a distance we go as straight as possible, thus assuming that light comes to us in a straight line from the object. To find whether three stakes or pins are in line we "sight" along them, for we know that light which just grazes two of them will also graze the third, if they are in a straight line. To test the straightness of a rod we glance along it to see if it is as straight as a ray of light.

An excellent illustration of the rectilinear propagation of light is afforded by a pinhole image. For example, an incandescent lamp in a box, one side of which is of pasteboard with a small hole in it, produces an image on a screen (Fig. 250) in a darkened room. The light from each point in the filament travels in straight lines through the hole, and forms a spot on the screen. The image is made up of these spots of light.

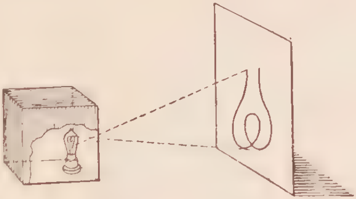


Fig. 250. Light Travels in Straight Lines

But light does not always travel in straight lines. Objects seem to flicker when seen over a hot stove or over sand on a hot day or through hot air escaping through a partly opened window. In these cases the rays from the object are bent. The air in which the light travels is not homogeneous, that is, not everywhere of the same temperature and density. Hence a more complete statement is this: **Light in a homogeneous medium travels in straight lines.**

How do you know light travels in straight lines? What is a pinhole camera? How is the image produced? Does light always travel in straight lines? Illustrate. What must be true of the medium transmitting the light if it is to travel in exactly straight lines?

291. Beams of Light and Rays of Light.—A very small source of light or a small part of a large source is called a *point source.* Any very distant light, even the largest star, looks like a bright point.

The light that starts from a point source and passes through an aperture in a screen is called a *beam* of light. A beam is described as "narrow" if the aperture is small compared with its distance from the source, other beams being described as "broad." A *ray* is a very narrow beam of light. It is often described as a "line of light," since light usually travels in straight lines, and in diagrams we represent rays by lines.

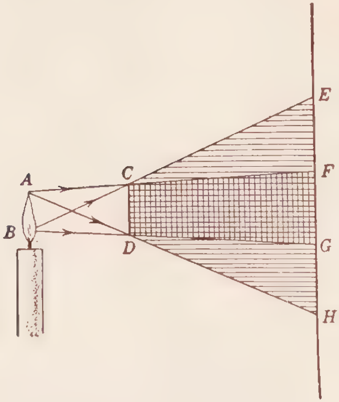


Fig. 251. Shadow, Showing Umbra and Penumbra

Define a point source of light. Distinguish between a beam of light and a ray of light. How are rays of light represented in diagrams?

292. Shadows.—The edges of the shadow of a body held in sunlight are sharp, because the sun is at a very great distance, and its rays are nearly parallel. But the edges of shadows are blurred if a candle or a lamp is the source of light and the object is near the source. The flame consists of a great many point sources of light, and these cast shadows that overlap.

A point in the blurred part, or partial shadow, receives light from a part only of the whole source (Fig. 251).

When the moon comes between the sun and the earth, it casts a shadow with blurred edges on the earth (Fig. 252*a*). An observer in the full shadow, or *umbra*, sees a **total eclipse of the sun,** but one in the partial shadow, or *penumbra*, which is many miles in width, sees a *partial eclipse,* part only of the sun being screened from him by the moon.

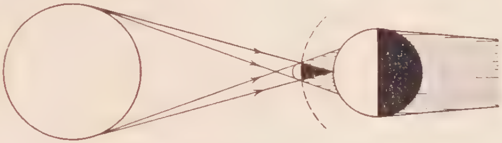


FIG. 252*a*. Eclipse of the Sun

When the earth passes between the sun and the moon, it casts a shadow on the moon (Fig. 252*b*) and causes an **eclipse of the moon.** Eclipses of the moon are more frequent than those of the sun, because the earth is much larger than the moon and casts a wider shadow.

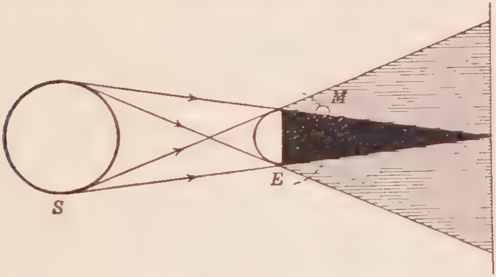


FIG. 252*b*. Eclipse of the Moon

What is a shadow? Are the edges of all shadows clear and sharp? What causes the blurring of the edges of the shadows? Define umbra and penumbra. How is a total eclipse of the sun caused? A partial eclipse? How is an eclipse of the moon caused? Why are eclipses of the moon more frequent in a given place than eclipses of the sun?

293. Transparent, Translucent, and Opaque Bodies.—Substances such as glass and water, through which objects can be clearly seen, are described as *transparent.* Metals and many other substances do not seem to transmit light, and are described as *opaque*. There is, however, no sharp distinction between the two classes. Impurities may make water and glass partly opaque. Light does not penetrate to great depths in the ocean. On the other hand, very thin sheets of metal are not quite opaque. Gold leaf, for example, is partly transparent.

Ground glass, foam, and paraffin wax transmit light, but objects cannot be clearly seen through them. The light suffers many changes of direction in its passage, and the original direction is quite lost. Such bodies are described as *translucent*.

What is a transparent body or substance? A translucent one? An opaque one? Is any substance perfectly transparent? Explain. What causes some bodies to be translucent?

294. The Speed of Light.—All parts of a wide landscape can be seen *at once* by a momentary flash of lightning. The reflected light does not seem to take any time to come to us from the most distant object in the landscape. When a battleship is looking for an enemy miles away by flashing a powerful searchlight, no allowance has to be made for the time required for the light to go to it and return. Light evidently travels with enormous speed.

Galileo proposed a simple method for measuring the speed of light. An observer on a hill was to find the time between sending a flash of light to an assistant on another hill and receiving an answering flash. The time, however, proved so short that it could not be measured. This showed that either the distance had to be greatly increased or the time had to be measured much more accurately.

It occurred to Ole Römer, a Danish astronomer, that a much greater distance could be used by observing the eclipses of one of the satellites or moons of the planet Jupiter. Once in a revolution a satellite T (Fig. 253) passes into Jupiter's shadow and is eclipsed. Römer observed the interval between two such eclipses when Jupiter was at its least distance from the earth. From this he could calculate the times at which later eclipses were to be expected, if light took no time to come from Jupiter to the earth. But they fell more and more behind the predicted times, just as letters posted from a train that is speeding away from us across the continent are more and more delayed in reaching us. When the distance was greatest Römer found the delay was 996 seconds (we now know it to be more nearly 1000 seconds). Since the earth had moved from E to E_1 and Jupiter from J to J_1 the distance between them had increased by the diameter of the earth's orbit, which was known to Römer (186 million miles). Hence Römer was able to calculate the speed of light.

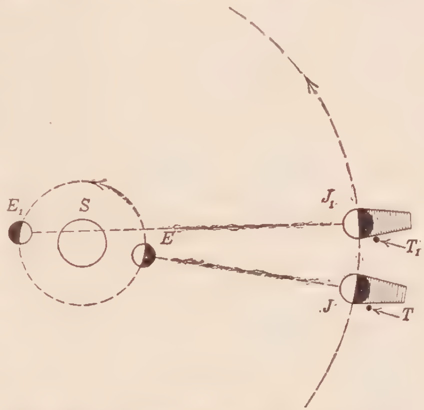


FIG. 253. Determining the Velocity of Light

Others followed the second plan for improving Galileo's method, and devised accurate methods for measuring short intervals of time. The results of the different methods agree very well. The mean value may be taken as

186,000 miles per second.
or
300,000 kilometers per second

By the second method it was also possible to find whether the speed of light is greater or less in water than in air. A long tube with glass ends was placed so as to form part of the path of the light. It was thus found that the speed in air is about 4/3 that in water and about 5/3 that in carbon bisulphide.

How do you know that light travels at enormous speed? How did Galileo propose to measure the velocity of light? Why did he fail? Explain Römer's method of measuring the velocity of light. What is the accepted value in meters per second? In miles per second? Does light travel more slowly in water than in air? In carbon bisulphide? What is the ratio of the speed in air to that in water? In carbon disulphide?

295. Light Consists of Waves.—Newton believed light to be a stream of particles, or *corpuscles*, shot off by luminous bodies. Huygens, a contemporary of Newton, maintained that it consisted of *waves*. Many of the properties of light can be explained in either way, but there is one point on which they distinctly differ.

Waves can interfere and destroy each other. For example, a crest of one train of water waves, falling on a trough of another train, may fill it up and make the surface level at that point (Fig. 254). Sound waves can combine to produce silence (§ 172). If it can be shown that rays of light can destroy each other, producing darkness, it will be a proof that light is a wave-motion.

What was Newton's theory as to how light was transmitted? What was Huygens's theory? What test can be applied to determine which is the correct theory?

296. Interference of Light.—That light can interfere and produce darkness can be shown in many ways, of which the following is one of the simplest. Make two fine straight scratches *very* close together on a photographic plate, by means of a straight-edge and the point of a knife. The coating on the plate may be regarded as an opaque screen and the scratches as slits through which light can pass. Now hold the plate in front of the face, so that the slits are in line with one eye and a distant light. An incandescent lamp with a straight filament, parallel to the slits, is best, but an ordinary incandescent lamp, of which all but an edge is covered by a card, will serve. You will see a large number of bright bands, *with dark spaces* between (Fig. 255). The bands will be sharper, if you put a sheet of colored celluloid in front of the light. These bands, alternately bright and dark, are a proof that **light consists of waves.** Streams of corpuscles, passing through the slits, could not produce a large number of alternations of brightness and darkness at the eye.

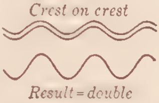


FIG. 254*a*.

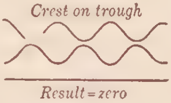


FIG. 254*b*.

When crest falls on crest there is reinforcement. When crest falls on trough there is destruction

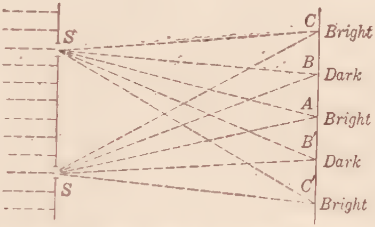


FIG. 255. Interference of Light Waves from Two Slits Producing Bright and Dark Bands

Since the two slits must be very close together, it seems evident that the waves of which light consists must be of very short wave length, even compared with the wave lengths of the short ripples on water or the wave lengths in the shrillest sounds. This has been confirmed fully by performing the experiment in a laboratory on a large scale, and making the measurements necessary for calculating the wave lengths. Many other, and better, methods have been devised for the same purpose. The results show that the wave lengths are indeed very small, and, further, that these wave lengths are different for lights of different colors, as is shown in the following table:

WAVE LENGTHS

Violet	.00040 cm.	Yellow	.00057 cm.
Blue	.00045 "	Orange	.00061 "
Green	.00052 "	Red	.00065 "

From this table it will be seen that the wave lengths are extremely small. It would take about 1000 wave lengths, on the average, to equal the diameter of a hair 1/50 of an inch thick.

What is meant by interference of light? How can it be shown to be possible? When you look at a light through two narrow slits very close together why do you see light and dark bands? What does this prove as to the nature of light? Why do the slits have to be very close together? How many wave lengths will equal about a fiftieth of an inch?

297. The Ether.—Waves are always transmitted by some medium, and the parts of the medium vibrate. Sound is a wave-motion in the air or some other form of matter. A bell vibrating in a vacuum gives off no sound, but light passes as readily through a bell-jar, from which the air and other gases have been removed by a pump, as it does through the air. Some incandescent lamps are made with a luminous metal filament in a vacuum. Light comes to us from the sun and the planets and from distant stars, and we know that there is no matter, in the ordinary sense, in the space in which the planets move, for it would, by its inertia, have long ago reduced the planets to rest.

These facts show that the medium which transmits light waves has not the ordinary properties of inertia and resistance to motion. Hence it is believed that there is everywhere a medium that is not what we have called matter, and that light is a wave motion in this medium. This medium we call *the ether.* It permeates all bodies, since, as we have seen, all bodies are more or less transparent.

What is always necessary in order to transmit waves? Is air the medium which transmits light? How do you know? What name is given to the medium which transmits light waves? Where is it found? How does it differ from ordinary matter?

298. The Relation of Waves and Rays.—The relation between waves and rays can be illustrated by a simple analogy. A company of soldiers on the march consists of a series of parallel ranks. These correspond to the wave-fronts. The line of march followed by each soldier corresponds to a ray. The line of march is perpendicular to the front. Similarly, rays are lines perpendicular to wave-fronts, and show the directions in which the energy of vibration is transmitted. This relation between wave-fronts and rays is shown by figure 256, where the vertical lines stand for wave-fronts traveling to the right, while the horizontal lines represent the rays at right angles to the wave-fronts.

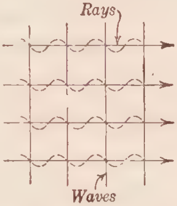


FIG. 256. Relation between Wave-Fronts and Rays

What is the direction of the front of a light wave compared to the direction the wave is traveling?

EXERCISES

1. What is the character of the light which enables you to see the objects and persons around you?

2. What is the character of the light that makes the sun visible? The moon? An incandescent lamp?

3. What is the source of illumination in an ordinary gas flame?

4. Mention one characteristic of most of our sources of light.

5. Why does a Bunsen flame become more luminous when salt is fed into it?

6. Why is a gas flame of natural gas less luminous than one of artificial gas? How could the luminosity of the former be increased?

7. What is the principle of the Welsbach mantle?

8. Is light itself visible?

9. Mention several practical applications of the fact that light usually travels in straight lines.

10. Why do distant objects apparently quiver when seen on a hot day?

11. Why do stars twinkle?

12. Show by a diagram how you could find the length of the sun's diameter by measuring the size of its image formed by a pinhole in a sheet of paper, assuming the distance of the sun to be known.

13. Explain the fact that an eclipse of the sun can be observed by watching the little patches of light that pass between the leaves of a tree and fall on the ground.

14. Why are pinhole images somewhat blurred?

15. What is a shadow? What is the penumbra? What is the umbra? What conditions are necessary to produce a penumbra? What conditions reduce the penumbra to a minimum?

16. Draw a diagram showing the shadow of a ball on a screen (a) when the shadow has no umbra, (b) when it has no penumbra.

17. Explain the phases of the moon.

18. What is a transparent body? A translucent body? An opaque body?

19. Name two examples of each. Mention a practical application of translucent bodies.

20. The Japanese frequently use sheets of oiled paper or silk for windows. What advantages do these have over glass?

21. Give two reasons why we sometimes use ground glass for windows.

22. If a perfectly transparent body existed, would it be visible?

23. What is the purpose of making the bottom third of some incandescent lamp bulbs of ground glass?

24. How could you tell when it is noon by measurement of the shadow of a plumbline?

25. What is the speed of light? How was it first determined?

26. Compare the speed of light and that of sound. If light traveled as slowly as sound, could the position of a battleship be found by flashing a searchlight on it?

27. If light traveled as slowly as sound, how would a landscape look when lighted up at night by a flash of lightning?

28. What is light? What was Newton's idea on the subject? How do we know that he was mistaken?

29. How do light and sound compare as regards wave lengths?

30. The statement is made that if the bright star Aldebarren had been destroyed 100 years ago, we would still see it shining in the heavens. Explain.

31. What do you mean by interference of waves? Have you ever seen such a condition? If so, describe it.

32. What important conclusion can be drawn from the fact that light can interfere?

33. How may the wave length of light be determined?

PROBLEMS

1. If a yardstick held vertically casts a shadow 1 ft. 8 in. long, how high is a flagpole which at the same moment casts a shadow 48 ft. long?

2. A certain pinhole camera consists of a box 6 in. cube, with the pinhole in the center of one side. If it is used to take a picture of a man 6 ft. tall, and 10 ft. from the camera how high will the picture be?

3. The circumference of the earth is approximately 25,000 miles. How long would it take light to travel this distance, and how far would sound travel in the same time?

4. The sun is at times 93,000,000 miles from the earth. How long does it take light to travel this distance? What effect has this on the apparent length of the day?

CHAPTER XXXI

INTENSITY OF LIGHT

299. Illumination.—Lamp-light falling on a book is less intense the farther the book is from the source, or the *intensity of illumination* decreases as the distance increases. By intensity of illumination we mean the amount of energy that the light carries to a sq. cm. of a surface in a second. It is difficult to measure this directly, but we can readily compare the intensities of lights from two sources.

Let S (Fig. 257) be a source of light. Since light travels in straight lines, the same light that falls on a card of 1 sq. cm. surface at a distance of 1 meter, would fall on a parallel card of 4 sq. cm. surface at 2 meters, and on one of 9 sq. cm. at 3 meters, etc. Hence, at distances as 1:2:3, etc., the intensities of illumination are as 1:1/4:1/9, etc., or **the intensity of illumination varies inversely as the square of the distance from the source.**

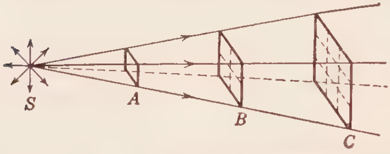


FIG. 257. The Law of Intensity of Illumination

Hence, if we wish to get the same illumination at a distance of 2 meters as one candle gives at 1 meter, we must use 4 such candles, placed close together, or a light of 4 *candle-power*, and to get this same illumination at 3 meters a light of 9 candle-power will be needed. In other words, **the candle-powers of two lights are as the squares of the distances at which they give the same intensity of illumination.**

Photometry or the Measurement of Light.—Light is a form of energy. Sunlight is energy that costs nothing, but gas and electricity have to be paid for. Hence it is important to be able to compare the amounts of light energy given off by different sources of light, or their illuminating powers. For this purpose two things are needed, a standard light and an instrument for comparing lights, just as a standard weight and a balance are needed for weighing.

The unit of illuminating power is the **candle-power.** A spermaceti candle that weighed one-sixth of a pound and burned 120 grains per hour was originally taken as a source of light of unit illuminating power. But for convenience of measurement we now use incandescent lamps, certified as to candle power by the Bureau of Standards in Washington.

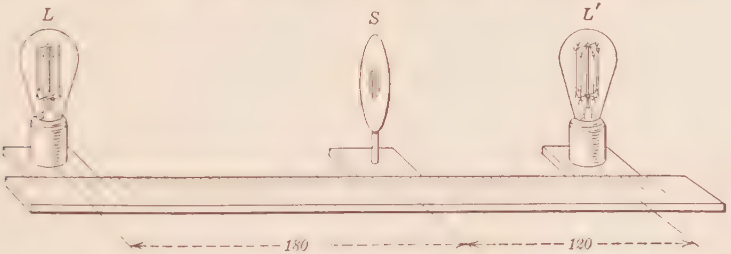


FIG. 258. Bunsen Photometer

The candle-powers of two sources of light are compared by applying the principle stated at the end of page 316. The lights are placed at such distances from a screen that they illuminate it with equal intensities. This is tested by a ***photometer.***

Most photometers are modifications of Bunsen's **grease-spot photometer** (Fig. 258). The essential part is a "screen," or disk of paper, on which there is a grease-spot. Light falling on the paper is mostly reflected, but light falling on the grease-spot is mostly transmitted. When the paper is held between the eye and a source of light, the grease-spot appears brighter than the paper, but it appears darker than the paper if your eye is on the same side of the paper as the light. This screen is placed between the lights, L and L', which are to be compared. When you look at the grease-spot from either side, say that on which L is, you *lose* that part of the light from L which the grease-spot transmits, but you *gain* that part of the light from L' which it transmits. When the screen is equally illuminated on the two sides, gain and loss just balance, and the grease-spot seems just as bright as the rest of the paper. Hence, if the distances of L and L' from the screen are adjusted until the grease-spot disappears, then the grease-spot is equally illuminated on the two sides, and the candle-powers of L and L' are as the squares of their distances from the screen. If L is a lamp to be tested and L' is a standard of 16 c.p., and if the two sides of the screen are equally illuminated when $LS = 180$ cm. and $L'S = 120$ cm., $L:L'::180^2:120^2$. Hence $L = 36$ c.p.

300. Calculation of Illumination.—For practical purposes the light that would be given by a lamp of one candle power at the distance of one foot is taken as the unit of illumination. This is called a **foot-candle.** Suppose now we wish to find the illumination by a lamp of 32 candle-power at 4 ft. At one foot it would give 32 foot-candles. Hence at 4 ft. it gives $32/4^2$ or 2 foot-candles.

A light that is too bright may be as injurious as one that is not bright enough. What is best depends on the individual and on the work. For reading this page 3 foot-candles would be about suitable for the average eye. How it could be obtained can be calculated by the method explained.

EXERCISES

1. State the law of inverse squares. Does it apply to any other physical phenomena than light?

2. When you hold a piece of unglazed paper in the center of which is a grease-spot, between you and a source of light, what is the appearance of the spot? Explain the cause of this appearance. What is the appearance when the paper is viewed from the other side? Explain the cause.

3. What is photometry? State how the Bunsen photometer is used.

4. What is the unit used in light measurement?

5. Explain by means of a diagram why the page of a book is most brightly illuminated when it is held perpendicularly to the rays that fall on it.

PROBLEMS

1. In using a photometer it is found that the grease spot disappears when the standard candle is 15 cm. from the screen and the lamp to be tested is 85 cm. from the screen. What is the candle-power of the lamp?

2. The total length of a photometer is 100 cm. If a standard candle is placed at one end, and a 25 candle-power light at the other end, where must the screen be placed so that the grease-spot shall be invisible?

3. If it takes 6 seconds to expose correctly a photographic print, when the print is 6 in. from the light, what will be the correct time when the print is placed 9 in. from the light?

4. I can get correct illumination for reading when the book is at a distance of 4 ft. from a certain lamp. How much greater should the candle-power of another lamp be to enable me to read equally well at a distance of 10 ft.?

5. A certain sign is illuminated by a lamp 10 ft. distant. What difference in illumination will result, if the lamp is placed 2 ft. nearer?

CHAPTER XXXII

REFLECTION OF LIGHT

301. Direction of Reflected Ray.—A ray *AB* of bright light, such as sunlight or light from an electric arc, is made clearly visible by dust in the air. Falling on a small mirror lying flat on a horizontal table *DE* (Fig. 259), it produces a reflected ray *BC*. The reflecting surface is the metallic back of the mirror, and this is in the plane of the top of the table. So far as the eye can judge the angles *ABD* and *CBE* are equal. This can be tested by taking points *D* and *E* on the table at equal distances from *B* and measuring the heights *DF* and *EG* at right angles to the table top. The optical disk (Fig. 260) shows the equality of the angles by a graduated circle. But the strongest

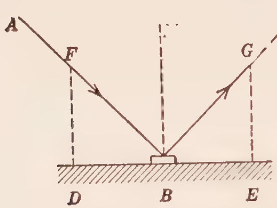


Fig. 259. Law of Reflection of Light

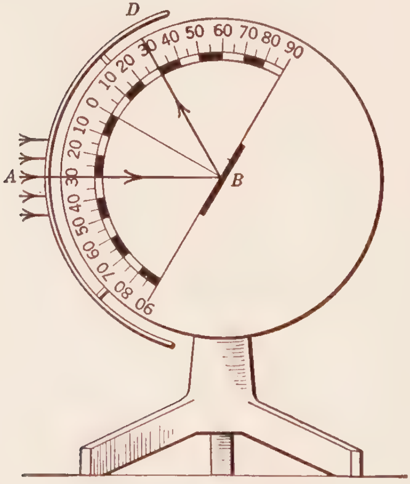


Fig. 260. Optical Disk

proof that the rays always make exactly equal angles with the reflecting surface is that many accurate instruments make use of this principle, for example the sextant, used in navigation (Fig. 261).

WIDE WORLD PHOTOS

FIG. 261. The sextant enabled Commander Richard E. Byrd to find his position in flying across the Atlantic in 1927

BN, the perpendicular to the reflecting surface, is called the **normal** to that surface (Fig. 259). The plane *ABN* containing the incident ray and the normal is called the **plane of incidence.** The angle *ABN* between the incident ray and the normal is called the **angle of incidence.** The angle *CBN* between the reflected ray and the normal is the **angle of reflection.** The laws of reflection are:

1. **The reflected ray is in the plane of incidence.**
2. **The angle of incidence is equal to the angle of reflection.**

These laws may be considered as a result of the reflection of waves. We have already learned (§ 166) that an incident plane wave *PQ* and a reflected wave *RS* make equal angles with the reflecting surface. Hence the rays, being perpendicular to the waves, also make equal angles with the surface (Fig. 262).

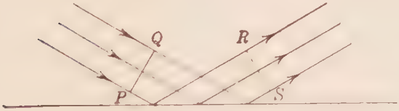


FIG. 262. Reflection of Wave from Plane Surface

How can a ray of light passing through air be made visible? If a ray strikes against a polished plane surface, what happens? How do the angles of incidence and reflection compare? Define: normal, angle of incidence, angle of reflection, plane of incidence, plane of reflection. State the two laws of reflection of light. How may these laws be verified?

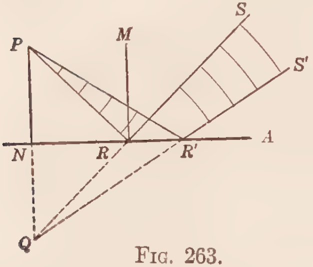


FIG. 263.

302. Images in a Plane Mirror.—The most familiar case of reflection is the image of the face and of other objects shown by a plane mirror. The image Q of a point P of the object seems as far behind the mirror as the point is in front of it. This is a result of the laws of reflection. For let PR (Fig. 263) be an incident ray, RS the reflected ray, and RM the normal at R. Draw PN perpendicular to the mirror and produce it to meet SR produced in Q. The angle QRN is equal to the angle SRA and therefore to the angle PRN. Hence $QN = PN$. Since this reasoning applies to any reflected ray, all rays seem to come from the same point Q, which is on PN and as far behind the mirror as P is in front. From this the method of finding the image of an object of any size and shape is evident (Fig. 264).

In figures 263 and 264 the parts of the waves from P that reach the eye are indicated. While it is easier to reason clearly by means of rays, it must not be forgotten that what affects the eye is the energy that reaches it in the form of wave motion.

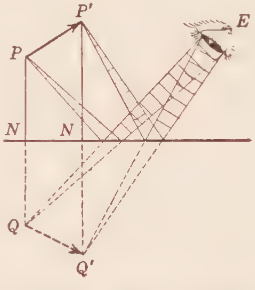


FIG. 264. Image in Plane Mirror

What is the most familiar example of reflection of light? Where is the image of an object which is in front of a plane mirror? Draw a diagram to show that the image is as far back of the mirror as the object is in front.

303. Diffuse Reflection of Light.—Light falling on a ceiling or wall is scattered in all directions. The surface of the plaster or paper is rough, that is, it consists of numerous small surfaces tilted in all directions, somewhat like crushed stone spread on a road. Each small surface reflects according to the laws of reflection, but there is no agreement of direction, and the light is sent in all directions (Fig. 265). But, when the surface of paper is very smooth, it acts to some extent like a mirror. When an airplane is several hundred feet above calm water, its image in the water can sometimes be seen and photographed from the airplane, but this is not possible when the surface is roughened by waves.

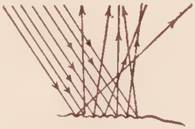


FIG. 265. Diffuse Reflection

Reflection of light by rough surfaces is called *diffuse reflection,* while reflection from smooth surfaces is called *regular reflection.*

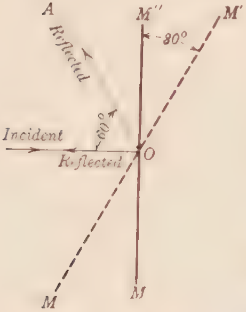


FIG. 266. Principle of Sextant

What happens to light which falls on a rough or uneven surface? Why is the light diffused? Why can you not see your image when you look at a rough surface? Define diffuse reflection.

304. Reflection from a Revolving Mirror.—When a mirror is held so that a ray of light falls perpendicularly on it, the ray is sent back in the direction from which it came. Revolving the mirror through 30° (Fig. 266) turns the reflected ray through 60°, as shown by the spot on ceiling or wall. This is because, for every degree that the mirror turns, the normal also turns one degree, and both the angle of incidence and the angle of reflection increase by one degree. Hence the angle between the incident ray and the reflected ray increases by two degrees. This principle is applied in the sextant, which mariners use for finding the elevation of the sun in order to obtain the latitude of the ship (*see* Fig. 261).

When light is reflected from a plane mirror and the mirror is turned through an angle of 5°, through what angle is the reflected ray turned? Show this by a diagram. What instrument makes use of this fact?

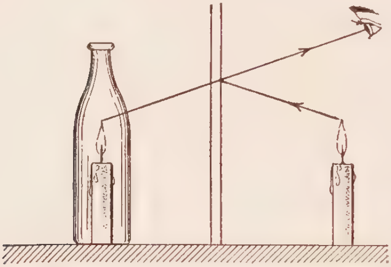


FIG. 267. Optical Illusion. Candle Burning under Water

305. Optical Illusions.—Many amusing optical illusions are produced by means of the reflection of light. For example, the appearance of a candle burning under water (Fig. 267) can be produced by means of a pane of glass, and a similar device has been used to show a ghost on the stage of a theater. Figure 268 shows how, by the use of four mirrors, a candle can apparently be seen through a brick.

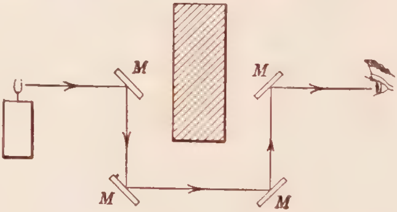


FIG. 268. Optical Illusion. Seeing through a Brick

What is an optical illusion? How may a candle be made to seem to burn in a tumbler of water? How may mirrors be arranged to make it appear that one can see through an opaque object? How are ghosts made to appear on a theater stage?

SPHERICAL MIRRORS

306. Spherical Mirrors.—A mirror in the form of a segment of a spherical surface is called a spherical mirror. If the reflecting surface is toward the center of the sphere, the mirror is **concave**; if it is away from the center, the mirror is **convex**.

The center, C, of the sphere of which the mirror is a part is called the **center of curvature** of the mirror (Fig. 269). The straight line CA through the center and perpendicular to the plane of the boundary is called the **principal axis.** Any other line as CE, through the center C is a *secondary axis.* The point A in which the principal axis cuts the mirror is called the **apex** of the mirror.

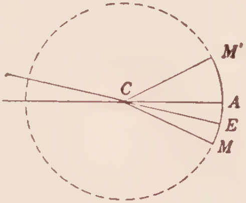


Fig. 269. Spherical Mirror

Concave mirrors are often made of very large size, in order to gather in a large amount of light and produce a bright image. The great reflector of the Mount Wilson Observatory (Fig. 270) is 100 inches wide. But the sharpness of the image formed by a mirror depends more on what

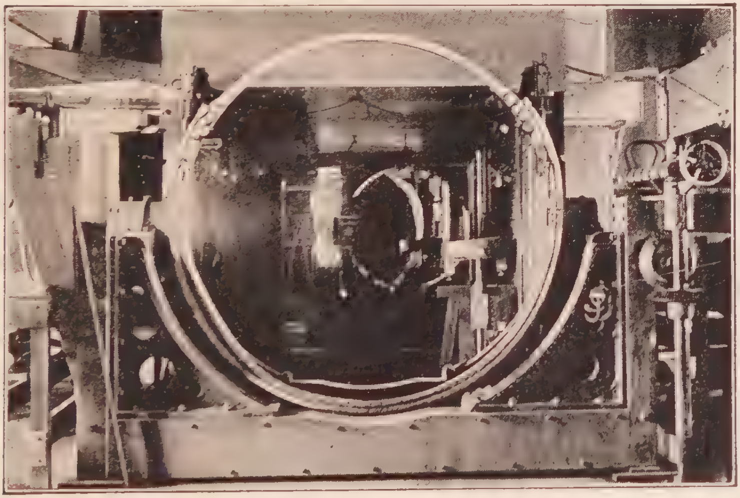


Fig. 270. Mount Wilson Reflecting Telescope
The 100-inch mirror, silvered and tipped forward on the turn-table for testing

is called the **aperture** of the mirror, that is, the size of the angle between radii to opposite sides of the boundary, or MCM' in figure 269. The image is sharper the smaller the aperture. We shall consider here only mirrors of small aperture, but in diagrams we have to exaggerate the apertures.

What is a spherical mirror? What is a concave mirror? A convex mirror? Define center of curvature, principal axis, secondary axis, and apex. What use is made of very large concave mirrors? What is the aperture of a mirror? What advantage has a mirror of small aperture over one of large aperture?

307. Concave Mirrors.—When parallel rays of sunlight fall on a concave mirror in the direction of the principal axis (Fig. 271), they converge, after reflection, to a bright spot on that axis, as can be seen by scattering chalk dust in the paths of the rays, or by holding a small card at the point. Heat concentrated there may ignite a piece of tissue paper or a match.

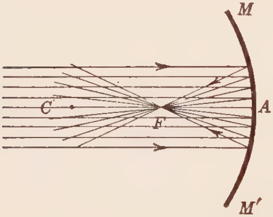


Fig. 271

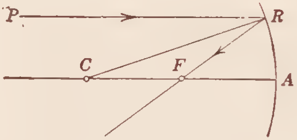


Fig. 272

Reflection in Concave Mirror

To explain this, consider a ray PR, incident at R (Fig. 272). Let F be the point in which the reflected ray cuts the axis. The angles CRF and CRP are equal, by the laws of reflection, and the angles CRP and RCF are equal, since PR is parallel to the axis. Hence the angles CRF and RCF are equal, and CF is therefore equal to FR. Since the aperture of the mirror is small (§ 306), FR may be taken as equal to FA. Hence CF and FA are equal. F is therefore a point on the axis, half way between C and A.

Since PR was taken as any ray parallel to the axis, it follows that all rays parallel to the axis pass, after reflection, through the point F.

The point in which the reflected rays cross, when rays parallel to the principal axis fall on a concave mirror, is called the **principal focus** of the mirror.

The distance of the principal focus of a concave mirror from the apex is equal to half the radius. This is called the **focal length** of the mirror.

If the parallel rays are not in the direction of the principal axis, they are in the direction of some secondary axis. This axis may be regarded as the principal axis of a somewhat larger mirror of the same radius. Hence the rays converge to a point on this axis, but, since the aperture of this larger mirror is greater, the focus is not so sharp.

What happens to parallel rays striking a concave mirror? If the rays are parallel to the principal axis, where will the bright spot be found? What is this bright spot called? Define principal focus of a mirror. Focal length of the mirror. How does an enlargement of the aperture affect the spot?

308. Diverging Rays Falling on a Concave Mirror.—When a point source of light is placed at such a position as P, in front of a concave mirror (Fig. 273), diverging rays fall on the mirror. Dust in the air or a card in the rays will show that the rays cross at a point Q between F and C.

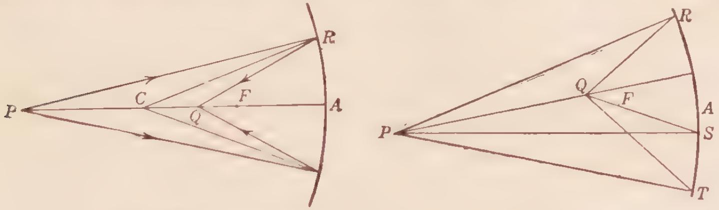


FIG. 273. FIG. 274.
Diverging Rays Reflected from Concave Mirror

If the positions of P and Q are marked and the source is transferred to Q, any ray QR must, after reflection, go to P. Hence all rays diverging from Q converge, after reflection, to P.

In figure 273 we have drawn P on the principal axis, but the reasoning would be exactly the same if P were on a secondary axis (Fig. 274), Q being on the same secondary axis.

Two points such that light diverging from one converges after reflection to the other are called **conjugate foci** of the mirror.

If the rays are not parallel but are diverging before striking the mirror, will they focus at the same point as before? If rays diverging from E meet at G, what will happen to rays diverging from G? What are two such points called? Define *conjugate foci.*

309. Real and Virtual Foci.—When a source of light is at a very great distance in front of a concave mirror and on the principal axis (Fig. 275), the reflected rays converge sharply to the principal focus F. When P is moved up towards the mirror (Fig. 276), the reflected rays converge to a focus Q,

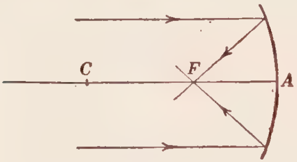


Fig. 275

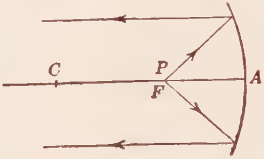


Fig. 277

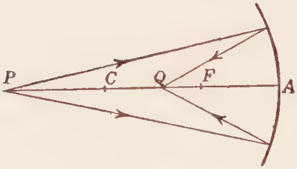


Fig. 276

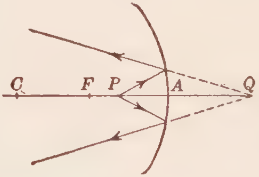


Fig. 278

When P is at an Infinite Distance from the Mirror (Parallel Rays), Q is at F. As P Approaches the Mirror, Q Moves from it, and is a Real Focus. When P is inside F, Q is behind the Mirror and is a Virtual Focus.

but less sharply. When the source is at *F* (Fig. 277) the rays do not converge, but go off parallel. Now let the source be moved to a point between *F* and the mirror (Fig. 278). On account of the increased angle of incidence, the reflected rays will become divergent, and will seem to come from a point *behind the mirror*, called a virtual focus.

A focus through which rays pass or from which they really come is called a **real focus.** A focus from which rays only *seem* to come is called a **virtual focus.** The images considered in connection with plane mirrors were all virtual images, as the rays only seemed to come from the points of the image.

What happens to the reflected light when the source is at the principal focus? If the source is nearer the mirror than the focus? Define a real focus. A virtual focus. Are the images formed by plane mirrors real or virtual images? Why?

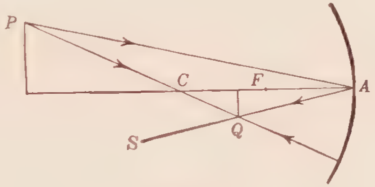


FIG. 279.

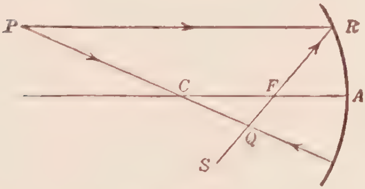


FIG. 280.

Methods of Drawing the Reflected Ray in Concave Mirrors

310. Methods of Drawing Reflected Rays.—Rays reflected by a spherical mirror can sometimes be drawn by simple graphical methods. By the law of reflection we see that a ray *PR* in a line through the center *C* is reflected back along the same line (Fig. 279), and a ray *PA*, incident at the vertex, *A*, is reflected in a direction *AS*, such that *PA* and *AS* make equal angles with the principal axis *AC*.

A second useful method is to make use of the property of the principal focus *F*. A ray *PR* parallel to the principal axis *CA* (Fig. 280) passes after reflection through *F*.

A ray passing through the center of curvature and striking the mirror is reflected in what direction? A ray striking a concave spherical mirror parallel to the principal axis is reflected through what point?

311. Images of Objects.—When an object is held in front of a concave mirror its image is

either upright or inverted
either magnified or diminished
either real or virtual.

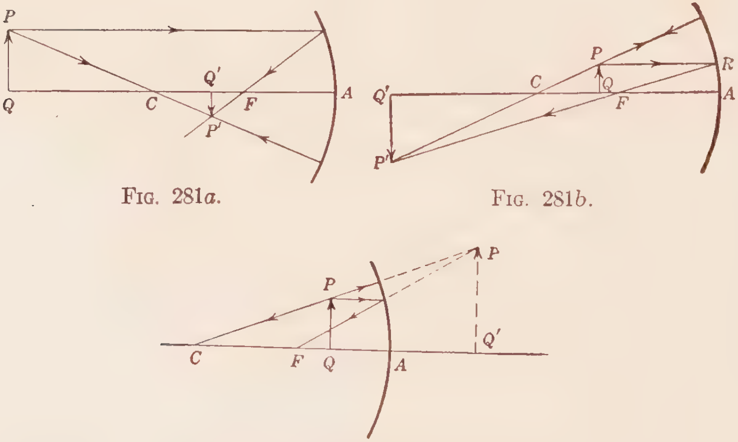


FIG. 281*a*.

FIG. 281*b*.

FIG. 281*c*.

Images in Concave Mirrors

For instance suppose an arrow PQ, is placed so that Q is on the principal axis, AC (Fig. 281). To find the image P' of P, let us draw a ray from P through C, and one from P parallel to the axis. P' is at the intersection of the two reflected rays.

When PQ is beyond the center C (Fig. 281*a*), its image $P'Q'$ is inverted, diminished, and real. When PQ is between C and the principal focus F (Fig. 281*b*), its image is inverted, magnified and real. When PQ is between F and the mirror (Fig. 281*c*) its image is upright, magnified, and virtual.

In all of these three cases **the lengths of object and image are to each other as their distances from the mirror.**

Are images formed by concave mirrors always alike? How may they differ? What kind of image is produced in each of the following cases: Object is beyond the center of curvature; object is between the center of curvature and the focus; object is between the focus and the mirror? What determines whether the image is magnified or not? Give the relation between the distances and the lengths of object and image.

312. Uses of Concave Mirrors.—The use of concave mirrors in *telescopes* of great power has already been mentioned. A small concave mirror is used to focus a strong light on an object that is being examined under a microscope. The *ophthalmoscope* is a concave mirror for reflecting light into a patient's eye, while the oculist looks into the interior of the eye through a small hole in the mirror. In the *laryngoscope* for examining a patient's throat, light, reflected from a concave mirror on the physician's forehead, is further reflected into the throat by a plane mirror at the back of the patient's mouth. The light that returns by the same path makes the throat visible.

Name three instruments employing concave mirrors. What is the purpose of the mirror in each case?

313. Convex Mirrors.—A convex mirror acts like a plane mirror that has been bent away from the incident light. It therefore reflects parallel rays so that they become divergent, and makes divergent rays more divergent. The images seen in it are therefore virtual, upright, and diminished (Fig. 282). Such a mirror is convenient for seeing a large field of view on a reduced scale. For example, a convex mirror, attached to the windshield of an automobile, shows cars on the road behind, and the images are upright and diminished.

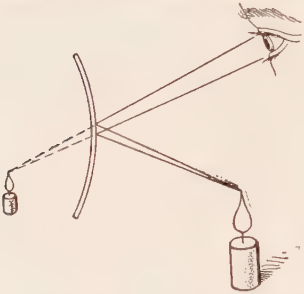


FIG. 282. Image in Convex Mirror

What effect has a convex mirror on parallel rays of light? What kind of images does a convex mirror produce? What uses are made of convex mirrors?

314. Caustic Curves.—Spherical mirrors of wide aperture do not form clear images. A strip of polished metal, bent into semicircular form, reflects light so that the rays cross in a spindle-shaped curve, called a *caustic curve* (Fig. 283). This is the explanation of the bright curve formed on milk in a glass by light reflected from the inside of the glass. It is well seen when a clear glass tumbler is inverted on a sheet of paper and held near a bright light.

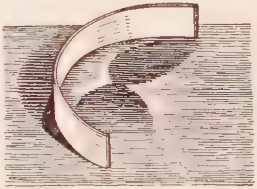


FIG. 283. Caustic Curve

The failure of rays to form a sharp focus, if the aperture of a mirror is wide, is called *spherical aberration by reflection.*

Are clear images produced by concave mirrors of large aperture? Why not? What is a caustic curve? How is it produced? Mention several ways of showing caustic curves. Define spherical aberration by reflection.

315. Parabolic Mirrors.—A concave mirror, the section of which is a parabola (Fig. 284), reflects parallel rays toward the axis, so that they intersect exactly at the focus of the parabola. Conversely, rays from a point source at the focus are reflected parallel to the axis. Such mirrors are useful for searchlights on battle ships, automobiles, trolley-cars, etc.

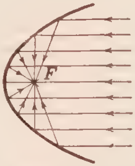


Fig. 284. Automobile Headlight

What is a parabolic mirror? What advantage has it over a spherical mirror? What uses are made of parabolic mirrors?

EXERCISES

1. Where must the light be placed in front of a concave mirror in order to obtain a parallel beam? A converging beam? A diverging beam?

2. State the conditions that will give a real image with a concave mirror. Will the image be erect? Will it be larger than the object? Illustrate your answers by diagrams.

3. State the conditions that will give a virtual image with a concave mirror. Will the image be erect? Will it be larger than the object? Illustrate by diagrams.

4. What kinds of images can be obtained from a convex mirror?

5. Why is a parabolic mirror better than a concave spherical mirror for a searchlight or a headlight?

6. State a number of applications of concave mirrors.

7. Make careful drawings of the image of a candle placed in front of a concave mirror, when the candle is (a) beyond the center, (b) between center and principal focus, (c) between principal focus and mirror.

8. Explain the sparkle of water in sunlight. Why is a bright summer day at sea apt to be trying to the eyes?

9. State the laws of reflection of light. Do these laws apply to diffuse reflection? Explain.

10. In general should a library be painted in a dark or a light color?

11. Explain, with the aid of a diagram, why two mirrors at right angles to each other will give three images of a candle placed between them.

12. If an object is viewed obliquely in a thick glass mirror, several images can sometimes be seen, at different distances behind the mirror. Explain, with the aid of a diagram.

13. At the World's Fair in Chicago, a triangular room was built, the walls of which were covered by mirrors. One person in this room saw many images of himself. Explain.

14. Mention all the applications of plane mirrors with which you are familiar.

15. A building seen by reflection in a pond is inverted. Explain this by means of a diagram.

16. Draw a diagram to show why a man sees a horizontal image of himself, if he stands in front of a mirror inclined at 45° to the floor.

17. How do you explain the illumination of a room in daytime, in the absence of direct sunlight?

18. Which do you meet the more frequently—regular reflection or diffuse reflection?

19. Why do photographers frequently paint the polished parts of machinery that is to be photographed?

20. Why are the heavens not illuminated at night?

21. How is it that you can trace the path of a sunbeam in a room?

22. Why does the general illumination in a moving picture theater seem to vary from time to time, as a picture is being shown?

SCHUYLKILL COLLEGE

CHAPTER XXXIII

REFRACTION

316. A Ray Is Bent in Passing into Water.—When a ray of light RC (Fig. 285) falls on water in a glass jar, it can be seen that the ray divides into two rays at the surface. One is reflected. The other passes into the water and is bent toward the normal to the surface. **If the refracted ray is reflected up from the bottom of the jar by a small mirror, it will, on emerging, be bent away from the normal.** Bending also takes place when light passes from air into glass or in the opposite direction, as can be readily shown by the optical disk (Fig. 260).

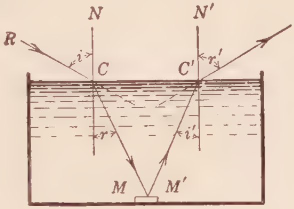


Fig. 285. Refraction

The change of direction of a ray of light in passing from one medium to another is called **refraction**. The angle that the refracted ray makes with the normal to the surface is called the **angle of refraction**.

When light passes from air into water or glass, the angle of incidence i is greater than the angle of refraction r. At C in figure 285, $i > r$. But when light passes from water or glass into air, the angle of incidence is less than the angle of refraction. At C' in figure 285 $i' < r'$. In both cases the angle in the air is greater than that in the denser medium.

What happens to a ray of light when it strikes obliquely on the surface of water? Which way is it bent? If it is coming out of the water, which way is it bent? What is this bending of the ray called? Define angle of refraction. Under what conditions is the angle of refraction greater than the angle of incidence? Smaller?

317. Examples of Refraction.—Place two cups, *A* and *B*, side by side (Fig. 286), and put a penny at the center of the bottom of each, and then fill *B* with water. If you stand back a distance, you will be able to see the penny in *B* while that in *A* is hidden. Moreover, the penny in *B* will seem higher up than that in *A*. The explanation is given by figure 285.

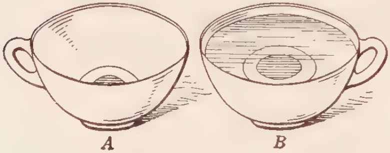


Fig. 286. Example of Refraction

Hold a lead pencil partly under water in a basin (Fig. 287*a*), and notice how the pencil seems bent at the surface. Refraction causes an apparent elevation of each part of the pencil under water.

These experiments show why a pond seems shallower than it really is, especially when it is looked at obliquely, and why an oar, partly in water, seems bent at the surface.

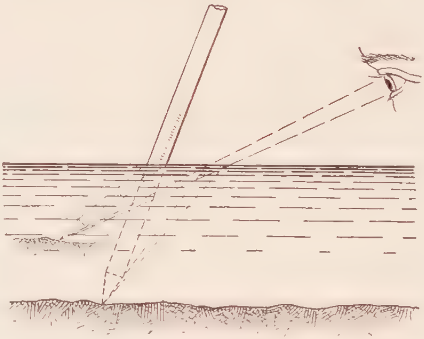


Fig. 287*a*. Example of Refraction

Mention ways in which refraction can be shown. Why does water look shallower than it really is?

318. The Laws of Refraction.—In designing microscopes, telescopes, and other optical instruments, a frequent problem is to find the direction of the refracted ray, when that of an incident ray is given. For this we need to know two things—

the plane in which the refracted ray lies and the angle which the ray makes with the normal.

Figures 285 and 287*b* indicate that the refracted ray is in the plane containing the incident ray and the normal, and this is confirmed by the most careful experiments.

A relation between the angle of incidence and the angle of refraction was discovered by Willebrord Snell in 1621. Let *RC* (Fig. 287*b*) be a ray incident at *C* on a surface *AB*, and let *ECF* be the normal at *C*. With *C* as center and *any* radius, draw a circle that cuts the incident ray in *P* and the refracted ray in *Q*. From *P* and *Q* draw perpendiculars *PM* and *QN* to the normal. The ratio *PM*/*QN* is evidently independent of the size of the circle, for if the radius were doubled both *PM* and *QN* would be doubled.

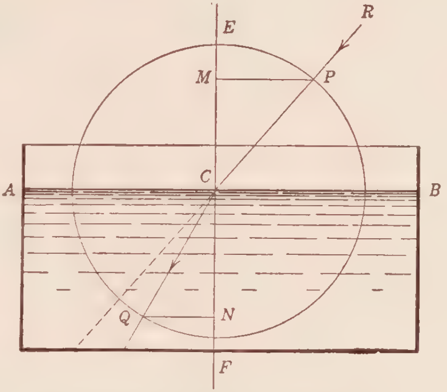


Fig. 287*b*. Laws of Refraction

Snell's discovery was that if light, traveling in air, be allowed to fall at different angles of incidence on water, the ratio *PM*/*QN* is the same in all cases. This ratio is called the *index of refraction* of water. The same is true if any other transparent substance be substituted for water, but the value of the ratio is different for different substances. It also differs somewhat with the color of the light (§ 334) but for the present we assume an average value for white light of 4/3 in the case of water and 3/2 in that of glass.

The laws of refraction are:

1. **The refracted ray is in the plane of incidence.**

2. **Whatever the angle of incidence, the index of refraction is a constant for the same two media.**

The quotient PM/PC, where PMC is a right angle (Fig. 287*b*), is called the *sine* of the angle PCM and is written sin PCM. Similarly QN/QC is sin QCN. Since PC and QC are equal, PM/QN is the same as sin PCM/sin QCN. Hence

$$\textbf{index of refraction} = \frac{\textbf{sine of angle of incidence}}{\textbf{sine of angle of refraction}}$$

or if, when light passes from air into a substance, the angle of incidence is i, the angle of reflection r, and the index of refraction n,

$$n = \frac{\sin i}{\sin r}$$

What contribution did Willebrord Snell make to our understanding of refraction? Show by a diagram what is meant by the index of refraction. Define index of refraction. How much is the index of refraction of water? Of glass? State the laws of refraction. What is the sine of an angle? State the index of refraction in terms of the sines of the angles.

319. Passage of Light Through Glass Plates and Prisms.—When a ray $PQRS$ passes obliquely through plate glass (Fig. 287*c*), it is refracted twice. At the first refraction it is bent toward the normal, and at the second it is bent away from the normal. It comes out in its first direction, but is evidently displaced sidewise. The displacement is greater the thicker the glass, and the greater the index of refraction. A right-angled block of glass may be used to find the *index of refraction* of glass as follows:

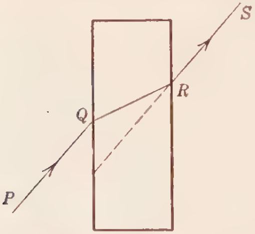


Fig. 287*c*. Refraction through Glass Plate

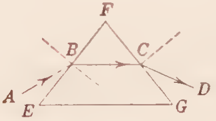


Fig. 287*d*. Refraction through Glass Prism

Draw a straight line *AB* on a sheet of paper (Fig. 288), and set the block with one face along the line. Stick a pin upright at *S* and in contact with the opposite face. Stick a second pin upright at *C* and in contact with the first face. Place a third pin at *P*, so that, when you look along *PC*, the three pins seem in line. Then a ray of light in the direction *SC* in glass emerges in the direction *CP*, or a ray in the direction *PC* in air would enter the glass in the direction *CS*. From this we can, by measurement, get *PM/QN*.

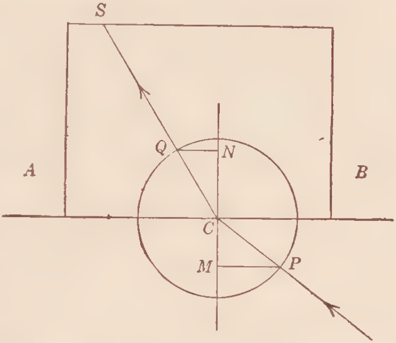


FIG. 288. Determining Direction of Refracted Ray

If the glass is in the form of an equilateral prism, the light is bent toward the thicker part of the prism when entering and also when leaving (Fig. 287*d*).

When a ray of light passes through a glass prism it is refracted at each of the two surfaces in accordance with the laws of refraction and is thereby bent toward the thicker part of the prism. The angle between its original direction and its final direction is called the *deviation* produced by the prism. The magnitude of the deviation depends on the kind of glass and on the angle of the prism. (Fig. 287*d*.)

Draw a diagram to show how the index of refraction of glass may be found. Letter the diagram and state the index of refraction.

When a ray of light passes through a plate of glass with parallel sides, what happens to its direction on entering and on leaving? How does the emergent ray compare in direction with the incident ray?

What determines the amount of the displacement of the emergent ray?

320. Total Internal Reflection.—The light of a lamp or gas flame reflected from the surface of water in a tumbler is not bright, but if the tumbler be held above the level of the light and observed underneath the opposite side (Fig. 289), a brilliant reflection will be seen. In the first case the incident light is in air, while in the second it is in water. A similar effect may be seen by looking down into an empty test tube plunged in water. Also if a stoppered tube containing water (or better glycerin), with an air bubble in it (Fig. 290), be inverted in sunlight, the surface of the rising bubble will shine like polished silver.

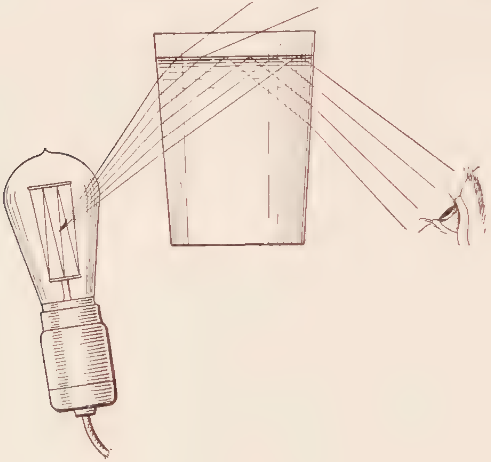


FIG. 289.
Total Internal Reflection

FIG. 290.

To find the explanation of these effects, let us suppose that rays of light, starting from a point Q in water (Fig. 291a), are incident at different angles on the surface. The angle of incidence increases from A to C. Hence the angle of refraction also increases. Somewhere, say at C, the angle of refraction becomes 90° and the emerging ray just grazes the surface. At D the angle of incidence is greater than at C, but the angle of refraction cannot be greater than 90°. Hence no light passes out; it is all reflected. This is called **total internal reflection.**

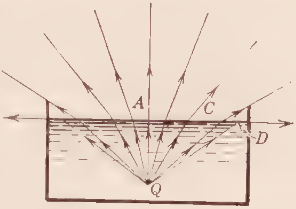
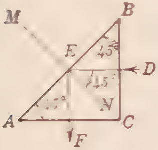
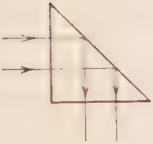


FIG. 291*a*. Total Internal Reflection Explained



The angle of incidence which is not exceeded by any ray that passes out of a substance is called the **critical angle** for the substance.



The critical angle for any substance can be calculated from its index of refraction n, since $n = \sin i / \sin r$. In this we put $i = 90°$ and then $\sin i = 1$. Hence $\sin r = 1/n$, where r is the critical angle. From this and a table of sines we get r. For water the angle is found to be 48.5°, for crown glass 43°, for flint glass 37.5°. The great beauty of the diamond is due to the fact that its critical angle is small, 24.5°, and it is therefore a brilliant reflector.

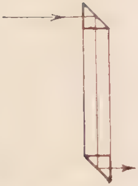


FIG. 291*b*. Periscope of Submarine

321. Examples of Internal Reflection.—Right angled glass prisms with equal unsilvered faces are useful as mirrors for turning a ray of light through 90° (Fig. 291*b*). If a ray passes in perpendicularly at one of the equal faces, it is totally reflected at the long face, since the angle of incidence (45°) is greater than the critical angle, and it passes out perpendicularly at the third face. This device is used in many optical instruments, especially in powerful field-glasses (§ 361). The periscope of a submarine (Fig. 291*b*) is a vertical sighting tube projecting above the surface of the water and having a right-angled prism at each end. By looking into the lower one an observer in the submarine can see over the surface of the water. Lenses are placed between the prisms to focus the light.

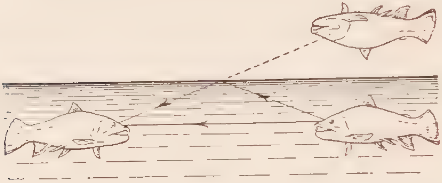


FIG. 292. What a Fish Sees

To an eye under water, for example the eye of a fish, some objects are seen by total reflection from the surface (Fig. 292). Thus another fish or part of the bottom may be seen by reflection as if the part of the surface beyond the critical angle were a mirror, so that an object below the surface seems to be above the surface.

Explain how you can cause light to be reflected from the under surface of water. In the case of light emerging from water, is the angle of refraction greater or less than the angle of incidence? If the angle of incidence be steadily increased, what finally occurs? Define internal reflection. Under what conditions does it take place? Define the critical angle. Why is a diamond so brilliant? Show how a right angled prism may be used as a mirror. Describe a periscope. Show by a diagram what a fish sees when he looks obliquely at the surface of the water.

322. Refraction of Plane Waves.—Let *a*, *b*, *c*, etc., be a train of plane waves, making up a beam of light, which falls on the surface *ST* of water or some refracting medium (Fig. 293). When each wave comes to the position *c*, it will begin to pass into the water at *C*, but the part at *D* will still have the distance *DB* to travel in air. While the wave is partly in air and partly in water, it will be bent into two parts as at *c′*; but when it is wholly in water it will again be a plane wave, as at *d*. The time from *C* to *E* in water is the same as the time from D to B in air. Since the velocity of light in water is less than its velocity in air (§ 294), CE is less than DB.

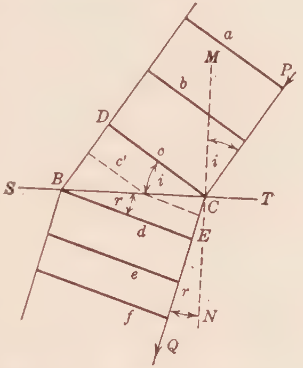


FIG. 293. Cause of Refraction

Thus each wave as it enters the water turns so that it is more nearly parallel to the surface ST. PC, the direction of motion in air, is perpendicular to a, b, and c, and CQ, the direction of motion in water, is perpendicular to d, e, and f. PC is the direction of an incident ray, and CQ that of the refracted ray. Hence the wave theory explains the change of direction of a ray as it passes from air to water.

The distance DB in air and the distance CE in water are traversed in the same time. Hence if we denote the velocity in air by V_1 and that in water by V_2,

$$\frac{DB}{CE}=\frac{V_1}{V_2}$$

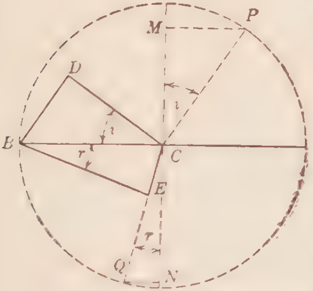


FIG. 294. Index of Refraction

The refraction of light as it passes from air into any other substance is explained in the same way. But the velocity of light is different in different substances. Hence V_1/V_2 has a different value for each substance.

Let us now combine the part $CDBE$ of figure 293 with the diagram of figure 287b for defining the index of refraction. The result is shown in figure 294. It is easily seen that the triangles PCM and BCD are equal in all respects, and also that the triangles QCN and CBE are equal in all respects.

Hence $PM = BD$ and $QN = CE$. From this and the last equation it follows that for any substance

$$\textbf{index of refraction} = \frac{\textbf{velocity in air}}{\textbf{velocity in substance}}$$

or, briefly,

$$\mathbf{n} = \frac{\mathbf{V}_1}{\mathbf{V}_2}$$

This relation can also be proved by noticing that in Fig. 293 the angle BCD is equal to i and CBE is equal to r. Then

$$n = \frac{\sin i}{\sin v} = \frac{BD}{CE} = \frac{V_1}{V_2}$$

From this result we see why the index of refraction of a substance is the same for all angles of incidence. For the velocity of light in any (ordinary) medium is the same in all directions.

By the aid of figure 293 explain why a wave of light is refracted on entering water or glass. Just what fact causes the refraction? Define index of refraction in terms of the velocity of light in the two media.

323. Relative and Absolute Index of Refraction.—In considering the refraction of a ray of light, we have so far supposed that air is one of the two media concerned. Refraction also takes place when a ray passes from water into glass or from any one medium into any other. In any such case the **relative index of refraction** of the two substances is defined by a geometrical construction as before, and it is also equal to the ratio of the speed of light in one medium to its speed in the other.

The index of refraction of a ray passing from air into a substance is a relative index for the two media. It also depends slightly on the state of the air. When it is necessary to be more precise, it is better to define the index of refraction of a substance on the assumption that the light passes from a vacuum into the substance. The index so defined is called the **absolute index of refraction** of the substance. It differs only very slightly from the index of refraction of the substance relatively to air. This is because the speed of light in air or any gas differs only very slightly from its speed in a vacuum.

Because the speed of light is so very nearly the same in a vacuum and in air, the absolute index of refraction of air is very nearly unity. But it is not exactly unity, and, moreover, it varies somewhat with temperature and density of the air. These properties of air are of great importance in the case of light passing long distances through the atmosphere.

Define relative index of refraction. What determines its value? Define absolute index of refraction of a substance. How does the speed of light in air compare with its speed in a vacuum? Is the speed in air always uniform? Of what importance is this fact?

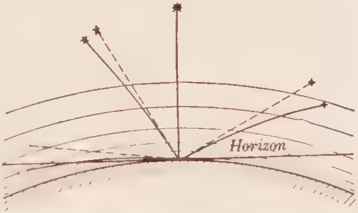


FIG. 295*a*. Atmospheric Refraction

324. Atmospheric Refraction.—The atmosphere surrounding the earth causes refraction of light coming from a star or from the sun (Fig. 295*a*). A star therefore seems slightly higher up than it really is. The setting sun can be seen for a short time after it is really below the horizon, and the rising sun appears before it reaches the horizon. The time from sunrise to sunset is thereby increased by 5 minutes near the equator, and more in higher latitudes.

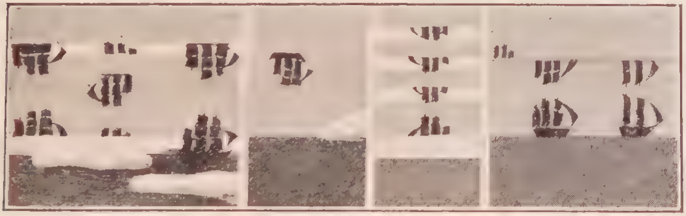


FIG. 295*b*. Mirages Sketched by Arctic Explorers

Mirages (Fig. 295*b*) are caused by bending of rays as they pass from cold to warmer layers of the atmosphere or in the opposite direction. For instance, a ship that is really so far away as to be below the horizon is sometimes seen inverted and suspended in the clouds. This is apt to occur when the air has been cooled by icebergs. For a similar reason trees or towns across one of the Great Lakes are sometimes seen apparently only a few miles away.

What effect does the atmosphere have on light passing obliquely through it? How can the sun be seen before it is really above the plane of the horizon? What effect does this have on the length of daylight? Explain how a mirage may be formed.

EXERCISES

1. Why does a pond seem shallower than it is when the bottom is seen obliquely from the shore?

2. Show by a diagram the reason for the distortion sometimes seen when objects are viewed through an ordinary window glass.

3. Explain, with the aid of a diagram why the sun is visible for several minutes after it is below the horizon.

4. What is the physical cause of a mirage?

5. How do you account for the phenomena of twilight and dawn?

6. A rectangular aquarium, when viewed from a corner so that two sides are visible, sometimes seems to contain more fish than it really does. Explain this.

7. How should a spear be directed to strike a fish under water?

8. State the laws of refraction.

9. Explain the cause of refraction on the view that light is a form of wave-motion.

10. When light is bent toward the normal in passing from one medium to another, what can you conclude as to the speed of light in the two media?

11. Show by a diagram how it would be possible for one fish to see another, though they were separated by a rock.

12. Draw diagrams to show the path of a ray of light through a periscope and through a prism binocular.

PROBLEMS

1. What is the speed of light in crown glass, the index of refraction being 3/2?

2. What is the ratio of the speed of light in water to that in crown glass?

3. Calculate the ratio of the speed of light in a substance, the index of refraction of which is n, to the speed in a substance the index of which is n'. Do you need to know the speed of light in air to do this?

4. When a ray of light passes from water into crown glass immersed in the water, what is the relative index of refraction?

5. Calculate the relative index of refraction when a ray passes from crown glass into carbon disulphide, the index of refraction of which is 1.64.

6. What is the speed of light in water, the index of refraction of which is 4/3?

CHAPTER XXXIV

LENSES

325. Forms of Lenses.—A lens is a transparent body with two curved faces or with a curved face and a plane face. Lenses are used in a great variety of optical instruments, such as microscopes, telescopes, and cameras, to form images.

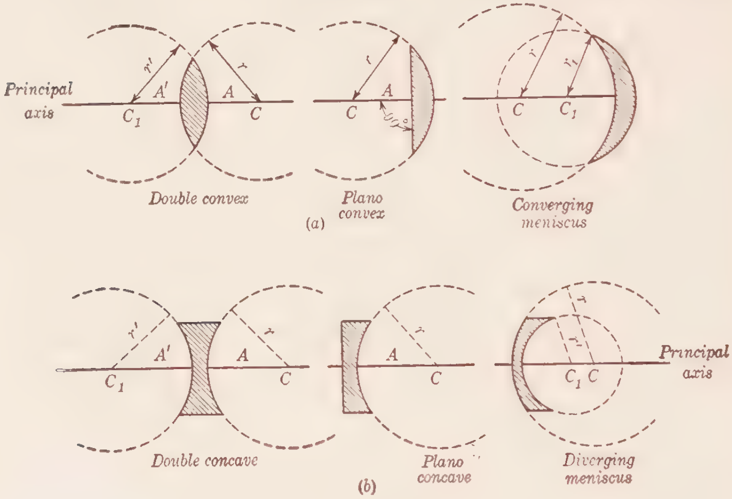


Fig. 296.

The curved face is usually part of a sphere, but special lenses are made with curved faces that are not spherical.

Six principal forms of lens can be formed by spherical and plane surfaces. These are shown, with the names by which they are known, in figure 296. The first three have sharp edges and are thickest at the middle. They are called **converging** lenses. The other three are thickest at the edges. These are called **diverging** lenses.

The center of the sphere of which a face is a part is called the **center of curvature** of that face. The straight line $CAA'C_1$ through the centers of curvature C, C_1 of the two faces, or through the center of curvature of one face and perpendicular to a plane face, is called the **principal axis** of the lens.

To produce sharp images, a lens must be *thin*, that is, its thickness must be much smaller than its width. We shall see the reason for this later (§ 332), and for the present we shall consider only thin lenses.

What is a lens? What is a converging lens? How many kinds are there? What is a diverging lens? How many kinds are there? Define center of curvature of a lens; principal axis of a lens. Diagram each of the six forms of lenses commonly used.

How a Lens Focuses Light.—To find how a plano-convex lens forms a focus, let us suppose that parallel rays fall perpendicularly on the plane face (Fig. 297). Consider two rays, PQ and $P'Q'$ at equal distances from the axis. Each passes into the glass without deviation. If the second face were plane, the rays would also pass out without deviation. But at the curved face each ray is bent away from the normal at the point, and they therefore meet at a point F on the axis. The

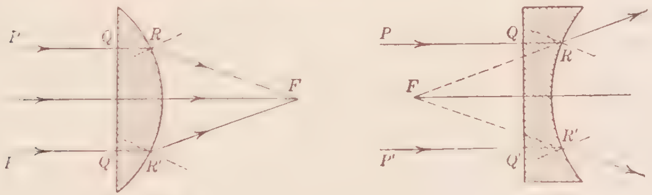


Fig. 297.

Fig. 298.

How Lenses Focus Light

bending at R and R' is greater, the greater the index of refraction of the glass. It is also greater, the more curved the surface is. Thus we see that the greater the index of refraction and the greater the curvature, the closer F is to the lens.

Let us now consider a plano-concave lens in the same way. In this case the directions of the normals at R and R' (Fig. 298) are such that the rays are bent away from the axis, so that they diverge, as if they came from a point F on the same side as the incident light.

In the plano-convex lens all the curvature is on one face. If we imagine it changed so that the curvature is shared between the two faces, the thickness remaining the same, it will become a double convex lens (Fig. 299) or a concavo-convex lens with F in the same position as before. Hence these three *converging* lenses act in the same general way. But the three forms show certain minor differences which fit them for different purposes in optical instruments. In a similar way we can think of the double concave lens and the convexo-concave lens as modifications of the plano-concave. All three are *diverging* lenses.

The point in which rays that were parallel intersect after passing through a lens is called the **principal focus** of the lens, and its distance from the lens is called the **focal length** of the lens.

A lens has a principal focus on each side and at equal distances from the lens. The principal focus of a converging lens is **real,** that is, the rays really pass through it; that of a diverging lens is **virtual,** that is, the rays only seem to come from it.

From figures 297 and 298 we see that **a ray passing through a lens is always bent toward the thicker part of the lens.**

Which way is a ray of light bent when passing through a lens that is thicker in the center than at the edge? What determines how much it is bent? If the lens is thicker at the edge than at the center, what happens to the light? Which kind of lens will bring the light to a real focus? Define principal focus of a lens. Define focal length of a lens. Is the principal focus of a diverging lens real or virtual? Why? State the general rule as to the direction a ray of light is bent on passing through a lens.

326. Pairs of Foci of a Lens.—Let us now suppose a point source of light P to be placed at the principal focus F of a converging lens (Fig. 299). This is the reverse of the case in Fig. 297, every ray being supposed reversed. Hence the rays emerging from the lens will be parallel. Now let P be moved away from the lens. Since the rays incident on the lens become less divergent, the converging lens will make them converge to a point Q on the opposite side from P (Fig. 300). The farther P is from the lens the closer Q will be to it. When P is at infinity, Q will be at F (Fig. 301). P and Q are called **conjugate foci.** In the cases considered Q is a *real* focus.

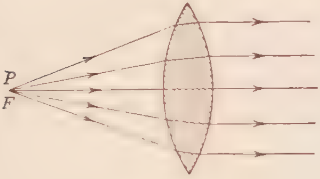


FIG. 299.

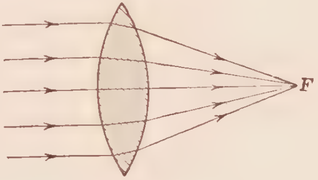


FIG. 301.

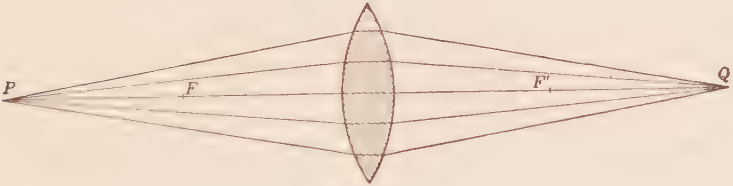


FIG. 300.

If P be placed at some point between F and the lens (Fig. 302*a*) the lens will not be able to make the rays converge.

They will therefore seem to diverge from a conjugate focus Q on the same side as P. In this case Q is a *virtual* focus.

A diverging lens (Fig. 302*b*) always makes diverging rays more divergent. Hence the focus Q conjugate to P is always virtual and between P and the lens.

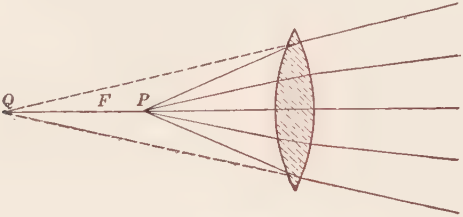


Fig. 302*a*.

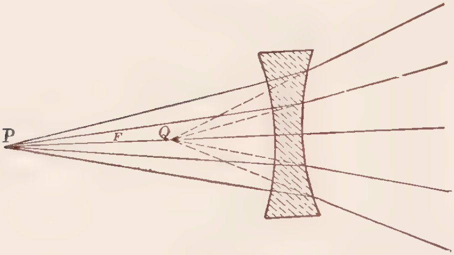


Fig. 302*b*.

Virtual Foci of Lenses

What happens if the source of light is at the focus of the lens? If it is nearer the lens than the focus? If it is farther away? Define conjugate foci. May a converging lens have a virtual focus? Explain by diagram. May a diverging lens have a real focus? Explain by diagram.

327. Secondary Axes of a Lens.—In figure 303 P is a luminous point, not on the principal axis. Rays from P to the upper part of the lens are bent or deviated in one direction, and those to the lower part are deviated in the opposite direction. There must, therefore, be an intermediate ray, incident near the middle of the lens, that is not deviated at all. Any line, other than the principal axis, such that a ray incident along it is not deviated by a lens, is called a **secondary axis** of the lens. Practically, for a thin lens, it may be taken as passing through the middle of the lens. The focus Q, conjugate to P, is on the secondary axis through P. The position of Q can readily be found, if the focal length of the lens is known. For if we draw a ray PR parallel to the principal axis, we know that, after passing through the lens, it must also pass through the principal focus F for a converging lens (Fig.

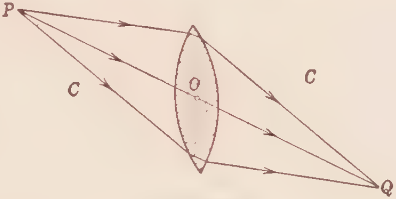


FIG. 303.

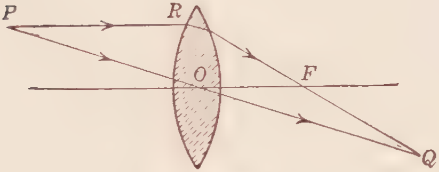


FIG. 304.

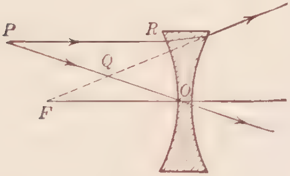


FIG. 305.

Secondary Axes of Lens

304), or seem to come from the principal focus F for a diverging lens (Fig. 305). We can therefore draw the ray, and its intersection with the secondary axis through P is the position of Q.

Define secondary axis. May conjugate foci be on a secondary axis as well as on the principal axis? Show by diagram.

328. Images of Objects.—The image of an object is made up of the images of the separate points of the object, and we have seen how the image of each point can be found.

I. Converging lens.

(1) When the distance of the object PQ from the lens (Fig. 306) is greater than the focal length of the lens, the image of each point is on the opposite side of the lens. Hence $P'Q'$ the image of PQ, is a *real image*. Since object and image are on opposite sides of the point in which the secondary axes PP' and QQ' cross, the image is an *inverted* one.

(2) When the distance of the object PQ from the lens (Fig. 307) is less than the focal length of the lens, the image $P'Q'$ is *virtual* and *upright*.

II. Diverging lens.

Rays diverging from a point of an object PQ (Fig. 308) are made more divergent by passing through a diverging lens. Hence the image $P'Q'$ formed by the lens is always *virtual* and *smaller* than the object. Since PQ and $P'Q'$ are on the same side of O, the image is always *upright*.

How is the image of an object made? When the object is more than the focal length from the lens, what kind of image is formed? Which side up is it? If the object is inside the focus, describe the image. Show each possible case by a diagram. What kind of image is formed by a diverging lens? What is its size? Which side up is it? Show by diagram.

329. The Lens Equation.—The position of Q can also be calculated by an equation which is found to hold true in all cases. In any of the cases in § 328 let us denote the distance of the object from the lens by p, the distance of the image by q, and the focal length by f. The equation connecting these is

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f},$$

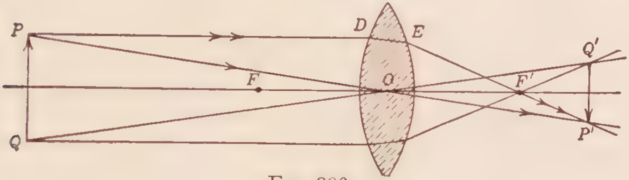


FIG. 306.

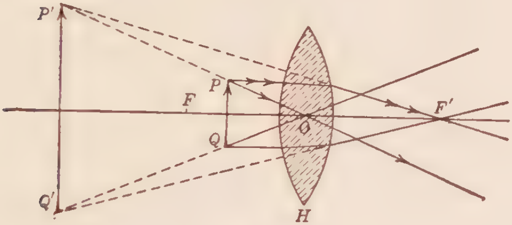


FIG. 307.

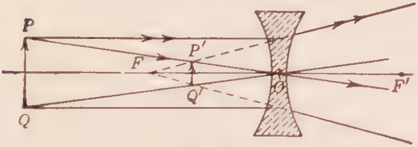


FIG. 308.

Position of Images in Lenses

and from this, when p and f are known, q can be found. To make the meaning of the equation clear let us consider some special cases.

(1) In figure 306 let us suppose that the focal length of the convex lens is 20 cm. and that the object is 60 cm. from the

lens. Then $p = +60$ and $f = +20$. Hence from the equation, $q = +30$.

(2) In figure 307 let the distance of the object from the lens be 15 cm. and let the focal length of the convex lens be 20 cm. Then $p = +15$ and $f = +20$. Hence, from the equation, $q = -60$.

From (1) and (2) we see that when q is found to be positive the image is *on the opposite side* of the lens from the object; that is, the image is *real;* but when q is found to be negative the image is *on the same side* of the lens as the object and is therefore *virtual.*

(3) In figure 308 let the distance of the object from the lens be 30 cm. and let the focal length of the diverging lens be 10 cm. Then $p = +30$. Since the lens is diverging, the principal focus for parallel rays on the same side as P is virtual, that is, F is on the same side as the object. Hence the value of f must be given a negative sign, and therefore $f = -10$. Substituting in the equation we get $q = -7.5$, the negative sign indicating that the image is on the same side as the object.

State the equation which gives the relationship of the distances of object and image in terms of the focal length. If a solution of the equation gives a negative value for the distance of the image, what do you conclude? What sign do you give the focal length for a diverging lens?

330. Size of Image.—In each of the figures in § 328 the triangles POQ and $P'OQ'$ are similar, and PQ and $P'Q'$ are therefore in the same ratio as their distances from O. Hence:

$$\frac{\textbf{length of image}}{\textbf{length of object}} = \frac{\textbf{distance of image from lens}}{\textbf{distance of object from lens}}$$

Upon what does the size of the image depend? State the equation which gives the relationship of the sizes and distances of object and image.

331. Passage of Waves through Lenses.—In considering how a lens forms an image, we have talked of the bending of *rays* by the lens. Let us now think for a moment in terms of *waves*. How waves of light are affected by passing through a lens is shown in two cases in figure 309. When waves spread from a luminous point and fall on a double convex lens (Fig. 309*a*), they become more curved in passing into the lens, and when they emerge they are curved in the opposite direction (if the source is not too close to the lens). They are then converging to a point, and this point is a real image of the source. If, however the expanding waves fall on a double concave lens (Fig. 309*b*), they become more curved in passing into the glass, and when they emerge they are still more curved. They then seem to have started from a point between the source and the lens. This point is a virtual image of the source. Thus the effect of a lens on a wave is to change its curvature. If the lens is a converging one, it can reverse the curvature of a wave, but a diverging lens always increases the curvature of a wave.

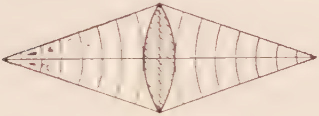


FIG. 309*a*.

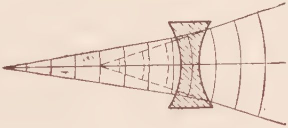


FIG. 309*b*.

How is the curvature of a wave changed by passing through a double convex lens? Through a double concave lens?

332. Sharpness of Images.—Some lenses form sharp, others somewhat blurred, images. One cause of the difference is shown by the following experiment. A glass bowl (Fig. 310) of the form of a hemisphere (or perhaps smaller) is placed on top of a glass jar, in which a drop of ammonia and one of hydrochloric acid form a faint mist of ammonium chloride. The bowl is filled with water, and sunlight (or arc light) is directed vertically on it. The rays form a spindle-shaped figure in the jar. This is a *caustic surface,* due to *spherical aberration,* or the failure of the rays to come to a sharp focus. That the rays from different parts focus to different points is shown by covering the bowl with a disk of pasteboard, in which there is a hole. By sliding the cover around, the different foci can be found. The water is a *thick* lens. If the water be removed, a cupful at a time, the lens will become gradually thinner, and the focus will steadily improve.

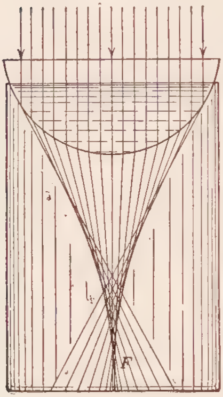


FIG. 310.
Caustic Surface

This shows why thin lenses are used in cameras, and why, for better definition, all except the central part of the lens is screened off.

How does spherical aberration affect the clearness of images? How may the effect be reduced to a minimum? Why are thin lenses preferred in cameras? Why are clearer images formed when a small aperture is used?

EXERCISES

1. What do the terms *converging* and *diverging* mean as applied to lenses?

2. How could you ascertain in the dark whether a glass lens is a converging lens or a diverging lens?

3. What is the center of curvature of a face of a lens?

4. What is the principal axis of a lens? What are secondary axes?

5. What is a real image? A virtual image?

6. What is meant by conjugate foci?

7. Why is it dangerous to place a spherical fish globe, filled with water, on a table in sunshine?

8. How would you test a spectacle lens to see whether it is a converging lens or a diverging lens?

9. Why are mirrors rather than lenses used to concentrate the rays in searchlights?

10. Draw a diagram to show the formation of the image of an object by a converging lens, (a) when the object is outside the principal focus, (b) when it is inside the principal focus.

11. Where must an object be placed with respect to a converging lens to produce a real image? A virtual image?

12. Is the real image in the last question necessarily larger or smaller than the object? Is the virtual image larger or smaller?

13. The cross section of a clinical thermometer is pearshaped with the thin edge toward the observer. Explain, with the aid of a diagram, the purpose of this.

14. If a card be placed to cover half of a convex lens, what effect will it have on a real image produced by the lens?

PROBLEMS

1. What is the focal length of a lens that will give an image 15 times as high as the object on a wall 10 ft. from the lens?

2. An object and its image are 100 cm. apart, and of equal size. Where is the convex lens that produces this result, and what is its focal length?

3. What is the height of a tree, 100 yds. away, when its image on a screen 1 ft. from a convex lens is 3 in. in height?

4. A child 3 ft. tall is 8 ft. from a camera which has a lens of 4 in. focal length. How high is the picture of the child?

5. An amateur photographer with a camera which has a lens of 8 in. focal length is 300 ft. from a yacht which is 120 ft. long. What will be the length of the image of the yacht on the photographic plate?

6. An object is placed 100 cm. from a converging lens, the focal length of which is 50 cm. Find the position of the image.

7. An object is 50 cm. from a converging lens of 100 cm. focal length. Where is the image formed?

8. An object is at a distance of 75 cm. from a diverging lens of 50 cm. focal length. Find the position of the image.

9. A camera is focused on a house 50 ft. away. The image is 4 in. from the lens. What is the focal length of the lens?

10. The focal length of one lens is 25 cm., of another 150 cm. Compare the *power* of the two.

11. An object is 20 cm. from a lens, and its image is 75 cm. from the lens on the same side. Find the focal length. What kind of lens is it?

12. How far must an object be from a converging lens, so that object and image shall be of the same size?

13. At what distance from a converging lens of 30 cm. focal length must an object be placed, in order that the image may be half as large as the object?

CHAPTER XXXV

SPECTRA

333. The Decomposition of White Light.—Before Newton's time, white light was regarded as the simplest light. Newton showed that it is in reality the most complex. Let us now consider his method.

When a beam of white light (sunlight or arc light) passes through a slit (Fig. 311) and falls on a screen it forms a white image, *W*, of the slit. If a glass prism, with its edges parallel to the slit, is placed in the path of the beam, the light is turned aside, or deviated, and forms a rainbow-colored band on the screen. This colored band is called a **spectrum** (Fig. 311). The end farthest from the original white image is violet, the other end red. The principal colors taken in order are violet, blue, green, yellow, orange, red, but these colors shade gradually into one another through intermediate colors. The spectrum may be considered as a series of images of the slit each in a particular color. This breaking up of white light into colored components is called **dispersion.** Since, as we have already seen, the different components differ in wave-length (§ 170) we conclude that **white light is a mixture of waves of different wave-lengths,** somewhat as the sound pro-

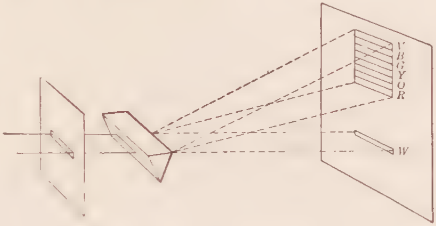


FIG. 311. A Spectrum

duced by striking all the notes of an octave on a piano is a mixture of the separate tones.

How may white light be separated into its component colors? Define spectrum. Name the colors of the spectrum in order. Define dispersion. What is the real difference between the colors?

334. Deviation and Dispersion.—In figure 312, showing the paths of rays in a prism, we have, for clearness, omitted all but violet and red. At *Q* the white light is separated into rays producing the different colors. Each ray is refracted toward the normal, the violet being refracted more than the red. The change of direction of the violet is therefore greater than that of the red. At *S* and *S′* the rays are refracted away from the normal, and again the change of direction of the violet is greater than that of the red.

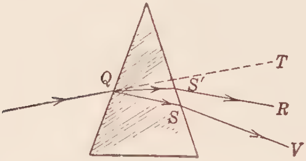


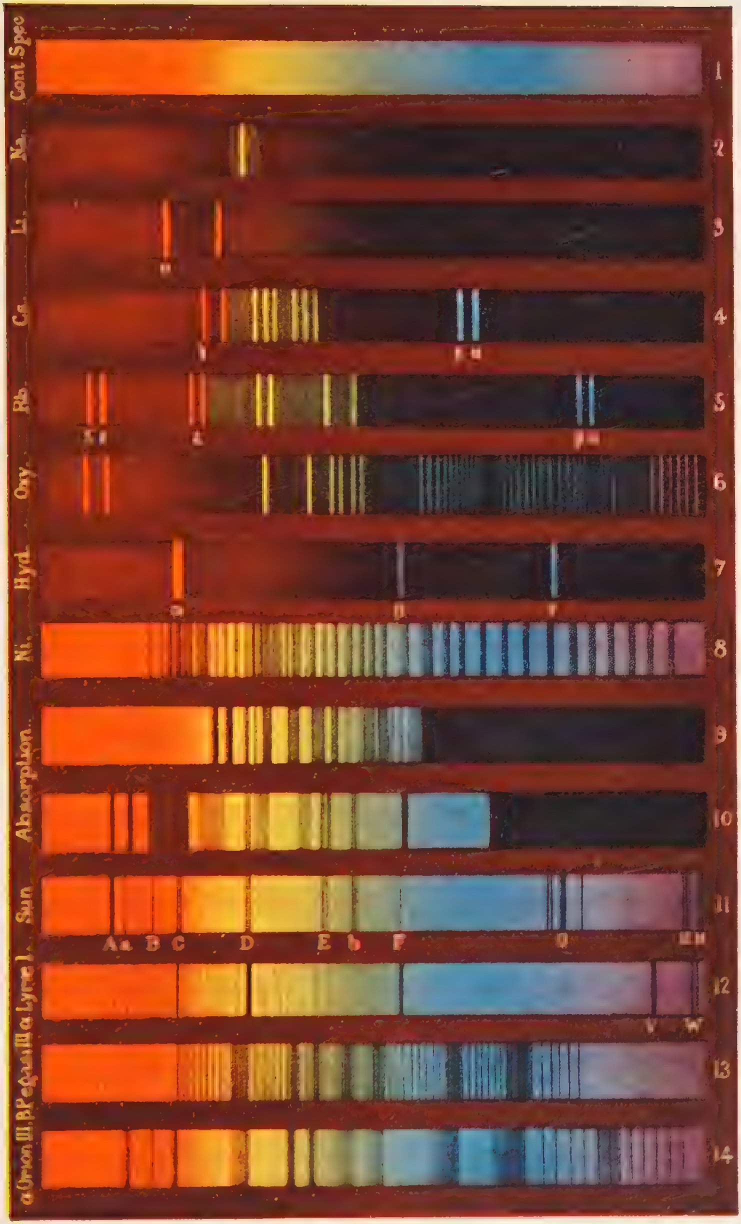
FIG. 312. Deviation and Dispersion

The **deviation** of the violet, or total change of direction, is the angle between *SV* and *QT*, that of the red is the angle between *S′R* and *QT*. The **dispersion** of violet and red is the angle between *SV* and *S′R*.

Why is white light dispersed in passing through a glass prism? Which color is refracted the most? Show by a diagram the deviation of the violet and red rays.

335. Velocity of Different Rays.—Glass refracts violet more than red. Hence the index of refraction of glass for violet rays is greater than for red rays, and the index decreases from the violet to the red end of the spectrum.

Now the index of refraction of any medium is equal to the ratio of the velocity of light in air to its velocity in the medium (§ 322). This applies to each color in the spectrum. A greater index of refraction indicates a smaller velocity in the medium.



Types of Spectra

From these statements we see that the velocity of violet rays in glass is less than that of red rays. The violet rays are of shorter wave-length than the red rays. Hence shorter wave-lengths travel in glass with less speed than longer wave-lengths.

From this we conclude that **dispersion is due to the different velocities with which waves of different lengths travel in the prism.**

Is the index of refraction of glass the same for red and violet rays? What does this show regarding the velocity of the rays of red? What does this prove regarding the length of the waves of red light? What is the fundamental cause of dispersion of white light?

336. Pure Spectra. The Spectroscope.—In the arrangement of figure 311 a wide slit must be used to get a sufficiently bright spectrum. Each color produces a wide image of the slit, and these colored images overlap.

For accurate work a narrow slit is used, and a bright light is placed close behind it (or light is focused on it). A converging lens is placed between the slit and the prism, at its focal length from the slit. A diverging beam of light falls on the lens and is made parallel before it falls on the prism. The rays emerging from the prism are again focused on the screen by a second converging lens. Hence each color produces an image of a narrow slit in the spectrum, and there is little overlapping. Such a spectrum is described as *pure*. If a very narrow part of the spectrum were lacking, a gap would be seen, whereas in the arrangement of figure 311 the gap would be covered up by other colors.

In the spectroscope (Fig. 313) the slit and one lens are in a tube. The second lens and a magnifying glass, or eyepiece for viewing the spectrum directly, are in a second tube. The two tubes can rotate on a horizontal circle, graduated in degrees, by which the directions of the rays can be found.

What is a pure spectrum? How may it be produced? Describe the spectroscope.

337. Different Kinds of Spectra.—*Continuous Spectra.*— The spectrum of light from an electric arc carbon is an unbroken band, extending from violet to red. Spectra of other incandescent solids and of molten metals are of this same general character. These are called continuous spectra. The light from a flame of illuminating gas is due to carbon particles in the flame, and its spectrum is therefore continuous.

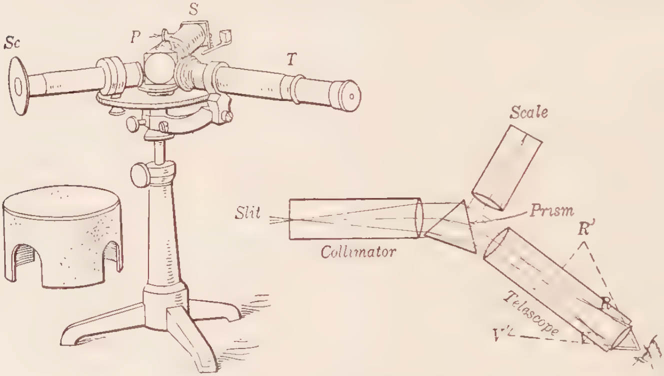


Fig. 313. Spectroscope

The spectrum, as *seen by the eye,* does not extend below red or above violet, but there are invisible parts of the spectrum far beyond these limits. The part beyond the red, called the *infra-red* part of the spectrum, shows it existence when a radiometer (§ 273) is placed in it. The part beyond the violet is called the *ultra-violet* part. It is found recorded on a photographic plate on which the spectrum is allowed to fall.

Line spectra. A Bunsen flame is only slightly luminous. But, when sodium chloride (common salt) is present in the flame, a strong yellow light is emitted. When the light is passed through a prism, it appears on the screen as a single

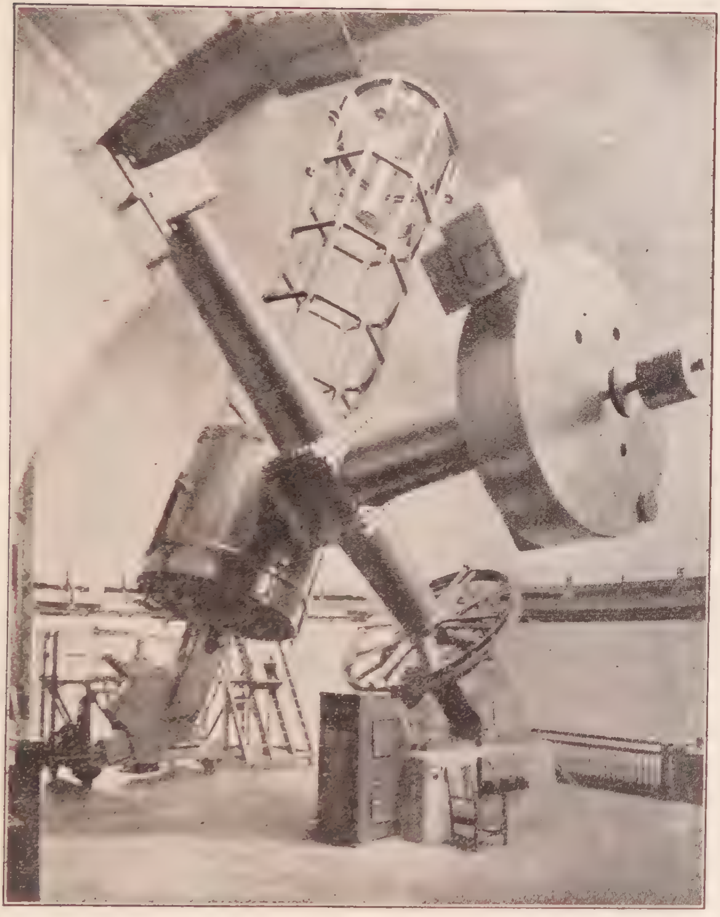


FIG. 314. The secrets of the stars are revealed by their spectra. This reflecting telescope, with a mirror 72 inches wide, was erected in British Columbia for the Study of Stellar Spectra
(Courtesy Encyclopædia Britannica Co.)

yellow *line.* The same yellow line is produced by any other salt of sodium in the flame. Hence this line is the spectrum of sodium. A salt of potassium in the Bunsen flame produces a spectrum that consists of a strong red line and weaker violet and yellow lines. Lithium, strontium, and all metallic elements have, when vaporized in a flame, their own characteristic line spectra. This is the basis of **spectrum analysis,** or the detection of the presence of substances by their spectra. Figure 314 shows the spectra of a number of elements.

Absorption spectra. When a continuous spectrum is formed on a screen, and a colored transparent body, glass, celluloid, or a liquid, is placed between the slit and the prism, gaps are produced in the spectrum. These are caused by the substance absorbing some of the constituents of white light. The parts of the spectrum absorbed by each substance constitutes its *absorption spectrum.*

What is a continuous spectrum? What produces it? What is a line spectrum? How may it be produced? What is an absorption spectrum? How may it be produced? What is spectrum analysis?

338. Resonance and Vibrations of Atoms.—There is one very important relation between line spectra and absorption spectra. *A substance absorbs light of the same wave-length as that which it can emit if heated.* As an illustration, let us suppose that the line spectrum of sodium is formed by placing, behind the slit (Fig. 315), a Bunsen flame, containing sodium or a salt of sodium, and that the position of the bright sodium line on the screen is noted. While there is still sodium vapor in the flame, let an arc light be started behind the flame. The spec-

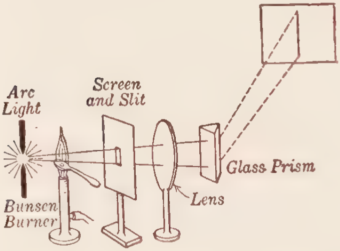


Fig. 315. Reversal of Sodium Line

trum of white light will appear on the screen, except that there will be a dark line exactly where the sodium vapor gave a bright line. The vapor in the flame acts as an absorber to the light from the hotter carbon in the arc.

This is very similar to the principle of *resonance* in sound (§ 168); a piano wire can take up the note that it can emit. It is strong evidence that light of each wave-length in the spectrum is due to something in the source of light that vibrates with a definite frequency. There is good reason to believe that it is not the atom itself that vibrates, but smaller parts (electrons) inside the atom.

How does the absorption spectrum of sodium compare with the line spectrum of sodium? How can the relation of line spectra to absorption spectra be shown? What causes the absorption spectrum of a substance?

339. Spectrum Analysis of the Sun and Stars.—The spectrum of sunlight contains a great many fine dark lines. A small spectroscope will show many of them, a large spectroscope will show thousands. These are called **Fraunhofer lines** after their discoverer (1815). Their presence remained a mystery until the relation between line spectra and absorption spectra was discovered (1860), when it became evident that they showed the presence of absorbing vapors in the atmosphere of the sun or of the earth. The few Fraunhofer lines due to the earth's atmosphere are known. The other lines show that the sun contains at least 40 of the elements present in the earth. One element, helium, was in this way discovered in the sun before its presence in the earth was known.

Stars and nebulæ also send us light, and this can be analyzed in the same way. The stars in general have spectra similar to that of the sun, showing that they consist of much the same elements as the sun and the earth. The nebulæ have bright line spectra and consist chiefly of luminous gases.

What are Fraunhofer lines? How are they produced? What may be learned from them? How was helium discovered? How do the spectra from stars compare with the spectrum of the sun? How do the spectra of nebulæ differ from that of the sun? What substances are indicated in the nebulæ?

340. Recomposition of Dispersed Light.—Figure 316 represents two prisms of the same kind of glass and of equal angles, but with their refracting edges turned in opposite directions. *P* would deviate light from the left downward, and *P′* would deviate it upward, to an equal amount. The dispersions would also be equal and opposite. When light passes through both, it is first dispersed by *P* and then recombined by *P′*, and there is no resultant dispersion or deviation. In combination the two prisms are equivalent, in their effect on rays of light, to a plate with parallel faces.

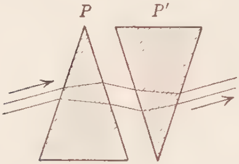


Fig. 316. Recomposition of Dispersed Light

Figure 317 represents two prisms of different angles and of different kinds of glass. *C* is a crown glass prism and *F* a flint glass prism of smaller angle than *C*. They oppose each other as regards both deviation and dispersion. When *C* has a given angle, an angle for *F* can be found, such that *F* just neutralizes the *dispersion* between violet and red due to *C*, but does not wholly neutralize the *deviation* due to *C*. Acting together they form a compound prism, which produces deviation without dispersion, that is, an *achromatic* (colorless) prism.

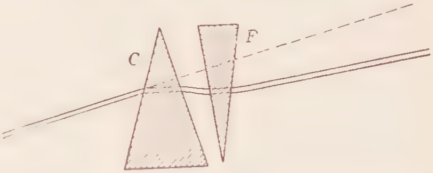


Fig. 317. Principle of Achromatic Lens

How can light dispersed by a prism be again brought together? Is it possible to have deviation by a prism without disperson? How can this be accomplished? What is an achromatic prism?

341. Achromatic Lens.—Where a ray of light passes through a lens, the small part of the glass adjacent to the ray may be regarded as part of a prism. Hence a ray of white light is dispersed as well as deviated, and the principal focus for violet is closer to the lens than that for red (Fig. 318). This defect of a lens is called *chromatic aberration.* It produces a certain indistinctness in the images of objects.

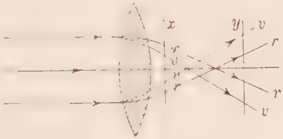


FIG. 318. Chromatic Aberration

To remedy the defect, a converging lens and a diverging lens of different kinds of glass are used in combination, being cemented together (Fig. 319). The curvatures of the faces are so chosen that the dispersion is as nearly neutralized as possible, but the deviation due to the converging lens is not wholy neutralized by the diverging lens. Hence the combination acts as an *achromatic lens,* giving uncolored images of white objects.

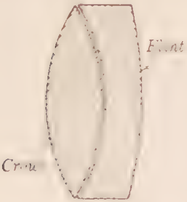


FIG. 319
Achromatic Lens

Do lenses cause dispersion as well as deviation? What objection is there to this dispersion? What is meant by chromatic aberration? How is an achromatic lens constructed?

342. Rainbows.—A rainbow is a spectrum of sunlight, the light being refracted and dispersed by water drops in a cloud. In the formation of the *primary rainbow*, a ray PQ, refracted into a drop at Q (Fig. 320), is dispersed, partly reflected at RV, and refracted out with further dispersion at $V'R'$. The violet is more deviated from the original direction PQ than the red is (§ 334). The violet rays and the red rays from

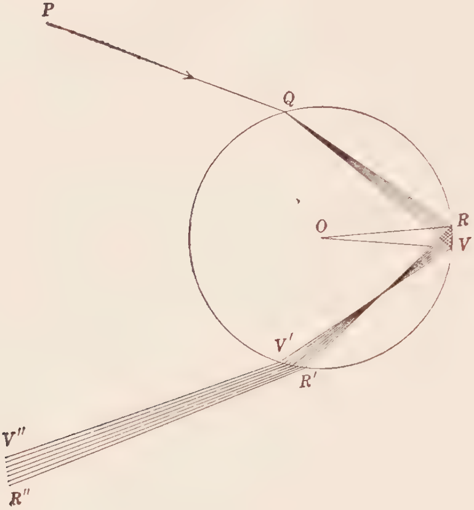


FIG. 320*a*. Rainbow Explained

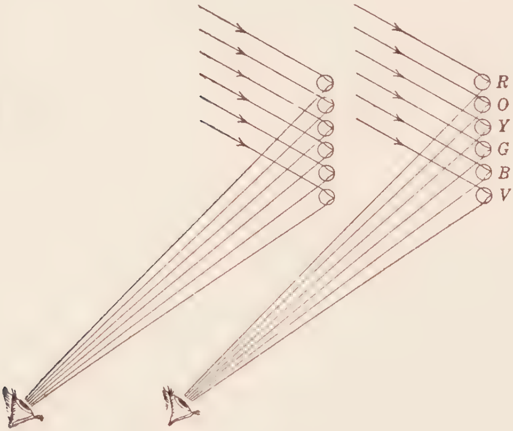


FIG. 320b. Do Two Persons See the Same Rainbow?

a single drop do not both enter the eye. Those which come to the eye come from different drops. From the figure it will be seen why the outside border of the primary rainbow is red and the inside violet.

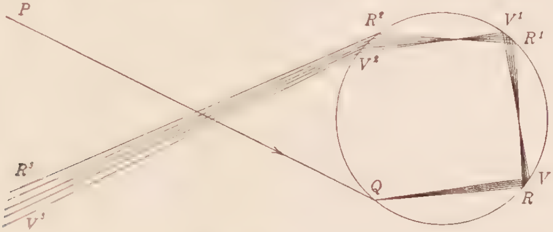


FIG. 321*a*. Secondary Rainbow Explained

The *secondary rainbow* is produced by light that has been twice refracted and twice reflected (Fig. 321*a*). Because of the two reflections it is weaker than the primary and is not seen so often. It is red on the inside and violet on the outside.

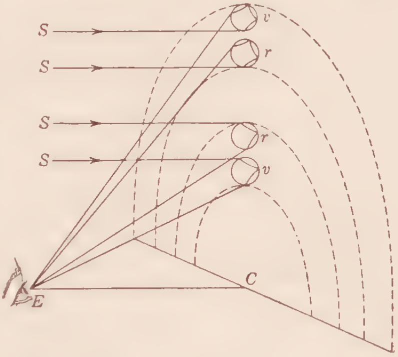


FIG. 321*b*. Primary and Secondary Rainbows

Explain what happens in a drop of water when a rainbow is formed. Which color is on the outside of the bow? Show by diagram. What is the secondary bow? How is it formed? Why is the secondary bow dimmer than the primary?

EXERCISES

1. What is meant by dispersion? What is the cause of it?

2. Explain the colors seen when the sun shines on raindrops clinging to a flyscreen.

3. Of what is white light composed? What is the source of the brilliant colors seen by looking through a prism?

4. If you look at a sheet of paper through a triangular prism it is red at one edge, blue at the other, and white in between. Why is this?

5. What is the fundamental difference between red light and blue light?

6. What is a spectroscope and for what is it used?

7. Name the different kinds of spectra.

8. What is the real source of light in a gas flame and what kind of spectrum should it give?

9. What kind of spectrum should moonlight give?

10. How are we able to determine the kinds of material of which the stars are composed?

11. Why are actors often surrounded by a colored halo, when seen through a cheap opera glass?

12. Sketch, describe and explain the formation of a rainbow.

CHAPTER XXXVI

COLOR

343. Pure and Mixed Colors.—When light that has been dispersed by a prism (Fig. 311) falls on the eye of an observer, each narrow beam produces a definite sensation of color—violet, blue, green, yellow, orange, and red—and each beam is of a definite wave-length. These spectral colors, each characterized by a definite wave-length, are called *pure* colors.

When white light falls on a red rose, some wave-lengths are absorbed, and their energy is turned into heat or chemical energy, while other wave-lengths are reflected. When the rose is held in front of the red part of a spectrum it is bright red, showing that it reflects pure red strongly. In the orange it is a weak orange, showing that it also reflects orange, but less strongly. In the yellow it is a very weak yellow. Hence the color of the rose in white light is due to the mixture of pure colors that it reflects. **It is red because it reflects red chiefly.** Leaves, ribbons, and other colored objects may be tested in the same way. Each reflects some one pure color strongly and others less strongly. Hence the color of an object depends on two things, the light that falls on it and the light that it reflects. When viewed in the *monochromatic* yellow light produced by salt in a Bunsen flame, all bodies are either some shade of yellow or black. The brilliant greenish light of a mercury vapor lamp makes the red parts of the face look black, because of lack of red in the light. A silk that is blue by daylight may be green by gas-light, because gas-light is deficient in blue.

Colors that seem identical to the eye may be due to different mixtures of pure colors. The housing of a cannon or other structures, painted green in warfare to imitate neighboring foliage (camouflage), can be detected from an airplane, by viewing them through suitable "color filters."

What is a pure color? Are most colors that we see pure colors? What happens when white light falls on a red object? Why does the object look red? How does a red object look in blue light? Why? What is a monochromatic light? How may such a light be produced? Why do not objects look the same by artificial light that they do by daylight?

344. Complementary Colors.—When white light has been dispersed by one prism and recombined on the screen by using a second prism (Fig. 316), a card can be inserted between the two prisms, so as to cut off part of the spectrum, and leave on the screen the mixed color due to the other parts of white light. If the two parts of the spectrum be cut off alternately by two cards, inserted from opposite sides, the mixed color due to each part can be shown separately on the screen. These two mixed colors in combination produce white. Colors that, when added, produce white are called **complementary colors.**

Two pure colors may also be complementary. A card with two narrow slits, inserted between the two prisms, will allow two nearly pure colors to pass. By trying cards with two slits at different distances apart, various pairs of complementary colors, such as blue and yellow, bluish-green and orange, green and red, can be found.

Colors can also be combined by painting them on a disk and rotating the disk at a high speed (Fig. 322). The colors are seen alternately many times per second, and this has the effect of combining them. Complementary blue and yellow on the disk give white. The rotating disk is one form of "color mixer," or device for combining lights of different colors.

You can find the color complementary to green in the following way, if a reading lamp with a green shade is available. Place a sheet of white paper on the table, so that the white light from the underside of the lamp shines on the paper. Gaze steadily at a point on the green shade for half a minute, and then look quickly at the paper. It will seem for a moment to be a bright red, the color complementary to green. This is due to *retinal fatigue*. The retina of the eye (§ 356) becomes fatigued or deadened to green by looking at it for a long time, but not to any other constituent of white light, so that when you glance quickly at the white paper, you are for a moment blind to green, and you see a combination of the other constituents of white light. By using shades or lamp bulbs of other colors, the complementary to any color could be found.

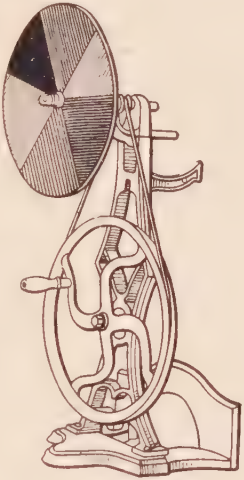


FIG. 322. Maxwell Color Disks

What are complementary colors? How may they be shown to be complementary? What is the complementary color of red? Of blue? Describe a color mixer.

345. Primary Colors.—When lights that are respectively violet-blue, green, and red in color are combined by a color mixer, any known color can be obtained by varying the proportions of these three constituents. These three colors are therefore called the *primary colors* (of lights).

What are the primary colors of lights? Why are they called primary colors?

346. Color Blindness.—The nerves of the eye are sensitive to the three primary colors, and all the varied colors seen by us are combinations of the three effects. In some eyes one set of nerves, say those which are sensitive to red, are defective, and we say that the person is red color-blind. About 4 per cent of men, but very few women, are color-blind to red. A color-blind person may call bricks red because he has heard them so described, but he does not see the same color as one of normal vision, and anything that affects the brightness of the light, such as fog, will cause him to confuse red and other colors.

Formerly many railroad accidents were due to color-blindness. On foggy nights, engineers who were more or less color-blind to red ran by red danger signals, thinking that they were green and so set for safety. Now every railroad tests applicants for the position of engineer, so as to be sure that no color-blind person is so employed. The test is usually made by requiring the candidate to select from a large number of colored wools specimens that match in color (Holmgren color test).

To how many distinct colors are our eyes sensitive? How then are other colors perceived? What is color blindness? How is it brought about? Why are prospective locomotive engineers examined as to color blindness?

347. Colors of Paints.—The color of a paint is usually a mixed color. When white light falls on blue paint, the paint reflects blue strongly, but it also reflects some violet and green. It absorbs the rest of the white light. A yellow paint reflects yellow strongly, green and orange weakly, and absorbs the rest. When these two paints are mixed and viewed in white light, the mixture *absorbs all except green,* which is therefore the color of the mixed paint. Thus the mixture of two *paints* gives different results from the mixture of two lights. The color of the paints is due to *subtraction* of colors, that of the lights to their *addition.* For this reason artists call blue, yellow and red the primary colors (of paints).

Blue and yellow lights mixed produce white light. Why do not blue and yellow paints produce white paint? What are the primary colors of paints?

348. The Color of the Sky.—One of the most familiar colors is the blue of the sky. Skylight is sunlight reflected backward and forward by dust particles or by water molecules or by the molecules of the air, before the light reaches the eye. At great heights in an airplane and on mountain tops, the sky is darker, because there is less of the atmosphere above to reflect.

The blue color is caused by the molecules reflecting more of the short waves of the spectrum than of the long waves, just as small obstacles in a pond reflect short water waves or ripples, but do not stop longer waves. This also explains why the sun, looked at directly, appears red near sunrise or sunset, for the red mostly comes through, while much of the blue is reflected away from us.

Why is the sky blue? Why is the sun red when near the horizon?

349. Colors Due to Interference.—When any one constituent of white light is removed, the rest form a colored mixture. Now we have seen in earlier experiments (§ 296) that waves can be destroyed by interference, the particular colors destroyed at any place depending on their wave-lengths.

This is the cause of the colors of a soap-bubble. A soap-film is readily formed on the mouth of a tumbler or on a ring of wire. When it is held with its plane vertical, it drains downward, and becomes thicker below than above. Hence it is a very thin wedge of water with reflecting faces, and interference takes place between waves reflected from the two faces. A similar explanation applies to the colors of films of oil on a smooth pavement, to those of mother of pearl, and to other similar cases.

How are the colors of a soap bubble caused? Why are they different in different parts of the bubble? What causes the colors of mother of pearl, opal, etc.?

EXERCISES

1. What is the action of red glass on white light falling on it?

2. Why are red objects red? What would be the color of a red rose, if viewed in a blue light?

3. In the greenish light of a Cooper Hewitt lamp most people look ghastly. Why?

4. Why does a greenish parasol, used in bright sunlight, seldom enhance the beauty of its user?

5. What would be the color of the light which had passed successively through pure red and pure blue glasses?

6. A tie that is blue by sunlight is black by the light from a kerosene lamp. Explain.

7. What is the color of seawater? Why? Is it red in the Red Sea?

8. In what parts of the world would you expect the sea to be most blue?

9. Why is the predominating color of the sky blue, but that of the sunset red?

10. What is the cause of the color of a soapbubble? Of mother of pearl? Of the film formed by oil on water?

11. Whence comes the color seen when a tool of polished steel is heated gradually?

CHAPTER XXXVII

OPTICAL INSTRUMENTS

350. The Projection Lantern.—The *condensing lens* of a projection lantern (Fig. 324) is a converging lens. It concentrates a large amount of light on a transparent object or on a lantern slide. Two lenses are usually employed for the purpose, because each does not need to be so thick, and is therefore less likely to be cracked by the heat. The *projecting lens* is an achromatic converging lens for throwing a large image of the object on a distant screen. Lanterns are also made for projecting opaque objects, such as a picture in a book. For this purpose a very powerful light is concentrated on the object, and an image is formed by the projecting lens as if the object were self-luminous (Fig. 325).

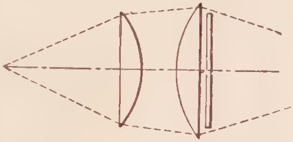


FIG. 323. Condensing Lens of Projection Lantern

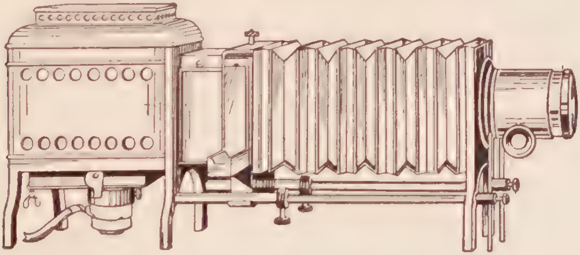


FIG. 324. Projection Lantern

A concave mirror is often used behind the source of light to increase the concentration of light on the object. A glass tank containing water placed behind the lantern slide will protect it from heating, for the water absorbs the heat while allowing the light to pass.

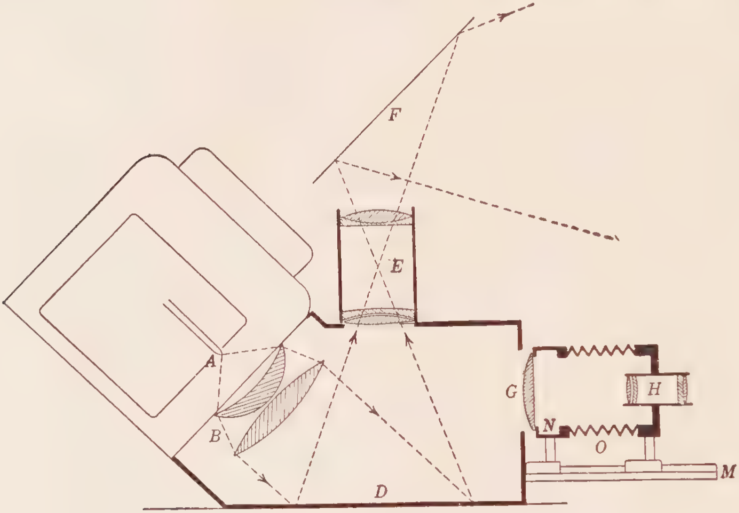


Fig. 325. Opaque Projector

What is the purpose of the condensing lens in a projection lantern? What is the purpose of the projecting lens? How may opaque objects be projected on the screen? What kind of mirror is used to increase the illumination? Why is a tank of water sometimes placed between the light and the slide?

351. Headlights for Automobiles.—The headlight of an automobile should throw a wide beam, so as to illuminate the road, but the light should be kept below a horizontal plane, so that it shall not dazzle the eyes of those who pass. Many arrangements have been devised for this purpose. An incandescent lamp is placed at or near the focus of a parabolic mirror, so that the light reflected by the mirror consists of parallel rays. This light then passes through a special form of "lens," which acts like a series of vertical cylinders combined with a prism, but is constructed of a single piece of glass. The light is thus spread horizontally, so that at a distance of 100 feet, the beam is about 50 ft. wide, while it is at the same time bent downwards on the road. A small amount of light passes directly from the lamp through the prism, but it is not sufficient to dazzle the eye.

What precaution is necessary in designing an automobile headlight? How is the desired result secured?

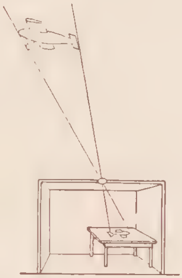


Fig. 326. Camera Obscura

352. The Camera Obscura.—This is a very old device that has been used in different ways. Its most recent application is for studying the motion of an airplane. For this purpose a large convex lens of long focus is mounted in the roof of a small building without windows (Fig. 326). The lens throws on a table below the lens a picture of the airplane, even when it is at a height of several thousand feet. In this way the flight of the airplane can be traced on paper, and its position at each tick of a clock can be recorded. The *camera obscura* was extensively used for sketching before photography was introduced.

Describe the camera obscura. What use is made of it?

353. The Photographic Camera.—In photography an image is formed by a lens on a "sensitized" surface (plate or film) and a permanent record of the image is thus obtained by chemical action. (Fig. 327.)

A simple converging *lens* gives a somewhat distorted image and disperses the light, producing some blurring. An achromatic lens (§ 341) is better, but a combination of two such, with a space between, is still better. In the space there is a *diaphragm* or stop with an aperture, the size of which can be varied to admit more or less light. By reducing the aperture, a sharper image is obtained, since rays that do not pass near the center of the lens are cut off (§ 332).

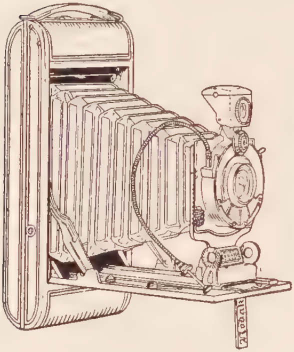


FIG. 327. Camera

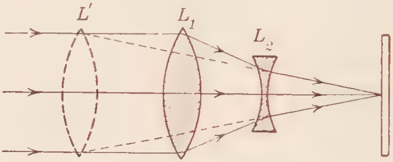


FIG. 328.

To get larger pictures of small distant objects a *telephoto lens* is used. (Fig. 328.) This is a convex lens L_1, with a concave lens L_2 behind it. The rays from L_1 are made less convergent by L_2 before falling on the plate. They seem to come from an imaginary lens L', equivalent to L_1 and L_2 acting together. The length of the camera is from L_1 to the plate, but it acts as if its length were from L' to the plate. It therefore takes a larger picture, without an inconveniently long bellows.

What is the purpose of the lens in a camera? What kind of lens is used? What is the purpose of the diaphragm? What effect does reducing the aperture have on the image?

354. Color Photography.—A transparent red gelatine screen, or "filter," as it is called, transmits all red light that falls on it, but absorbs green and blue. In the same way green and blue filters transmit green and blue lights respectively, and absorb the other colors. By photographing the same view through red, green, and blue filters, three negatives are obtained, and each is a record of the amount of one of the primary colors in the mixed light from any part of the view. This is the foundation of *color photography*.

To reproduce the original colored view, positives are made from the three negatives, and each is used in a triple projection lantern with a filter of the corresponding color. The superposition of the three colored pictures on the screen reproduces the original colored view. The results are true to Nature, but the process requires a special projection lantern.

What are color filters? How are they used in preparing colored lantern slides?

355. Autochrome Plates.—The autochrome plate uses the preceding principle, but the results can be viewed without a lantern. Starch grains are colored red, green, and blue, and are then mixed in such proportions that the mixture is grayish. This is used to coat a glass plate, and over it a color-sensitive photographic film is spread. The plate is then exposed in an ordinary camera, but with the glass side to the light, so that each colored grain acts as a color filter. On development, a negative is obtained that shows the view in the complementary colors. This negative is then dissolved, and the remaining sensitive film is exposed to light and then developed. The resulting negative transmits light of the original colors and we see a reproduction of the colored view.

How are autochrome plates prepared? What takes the place of the color filters? How are the plates developed?

356. The Eye.—The eyeball (Fig. 329) is roughly spherical and about an inch in diameter, with a small transparent curved projection, called the **cornea,** at the front. The eye may be thought of as a small camera. The **lens** is double convex and (with the aid of the cornea) forms real images on the sensitive surface called the **retina,** which lines the back of the eyeball. The **iris,** which shows as a colored ring, is a diaphragm with a variable aperture, called the **pupil,** for regulating the amount of light admitted. In front of the lens is a weak solution of common salt called the *aqueous humor,* and behind the lens is a jelly called the *vitreous humor.*

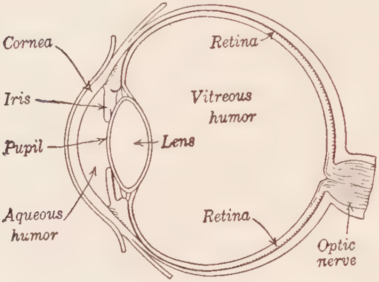


FIG. 329. Human Eye

The focus of the eye, like that of the camera, can be adjusted for distant and near objects. For this purpose a muscle that girdles the lens can be contracted or relaxed, so as to make the lens more or less curved. This process is called **accommodation.** Nature has also provided a means for forming a sharper image than a glass lens of the same shape would give; for the lens of the eye is denser near the middle than near the edge and brings all rays to nearly the same focus, so that spherical aberration is reduced.

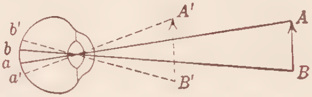


FIG. 330. How We See Small Objects

Communication between the eye and the brain takes place by means of the **optic nerve.** This consists of a bundle of nerve fibers, the ends of which spread out at the back of the eye forming the retina. Where the bundle of fibers passes out at the back of the eye, the retina is not sensitive. The *blind spot* can be found by the directions below (Fig. 331).

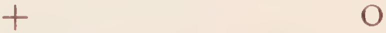


FIG. 331. Blind Spot

Close the right eye and hold the page so that the round spot is in the line of vision of the left eye and about 12 inches from it. Move the page toward you or away from you. The image of the cross becomes invisible when it falls on the blind spot of the eye.

A large object can be seen better than a small one, because the large object produces a larger image on the retina. To see a small object *AB* better we bring it closer to the eye and thereby increase the size of its image on the retina (Fig. 330). The size of the retinal image *ab* of an object *AB* depends only on the size of the angle *AOB*, which is called the *visual angle.* This angle may be taken as the measure of the *apparent* size of an object.

With reference to the eye define cornea, lens, iris, retina, pupil. What is the purpose of each? How is the eye focused for different distances? What is the process called? Why is the lens denser in the center than at the edges? What is the vitreous humor? The aqueous humor? What is the blind spot? How can you show it exists?

357. Defects of Vision.—The most common defect of the eye is in the focal length of the lens. If it is too great (Fig. 332*a*), distant objects may be focused sharply on the retina, but rays from a near object, such as a book held for reading, fall on the retina before coming to a focus. This is called **far-sightedness** (hypermetropia). The remedy for it is the use of converging lenses or spectacles, since a converging lens forms with the lens of the eye a combination of shorter focal length. **Near-sightedness** (myopia) occurs when the lens of the eye is of too short focal length. Diverging eye-glasses remedy this by increasing the effective focal length.

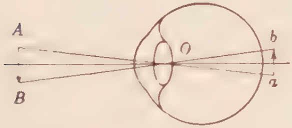


FIG. 322*a*. Far Sight

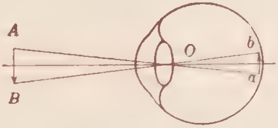


FIG. 322*b*. Near Sight

Oculists and opticians describe a converging lens as "positive," and a diverging lens as "negative." To state the strength or "power" of spectacle lenses, the *diopter* is used as unit. A lens is of one diopter power if its focal length is 1 meter, of 2 diopters if its focal length is ½ meter and so on. The power of the lens of the human eye is about 40 diopters.

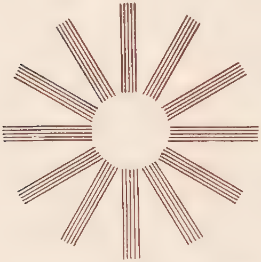


Fig. 333. Lines to Test Astigmatism

In some eyes the surfaces of the lens (and cornea) are so far from spherical, that an incident pencil of parallel rays is not refracted to a single point, that is, it becomes *astigmatic.* Lines in certain directions in a diagram may be seen clearly, while lines in other directions are blurred (Fig. 333). This defect, which is called *astigmatism,* is remedied by using glasses that are more or less cylindrical.

What is the most common defect in the eye? How is far-sightedness remedied? What causes near-sightedness? How is it remedied? How is the strength of a spectacle lens rated? What is a lens of 2 diopters? What causes astigmatism? How is it remedied?

358. The Magnifying Glass or Simple Microscope.—To see a distant object more distinctly, we bring it toward the eye, so as to form a larger and brighter image on the retina. But it must not come too close, or the lens of the eye will not be able to focus it on the retina. There is therefore for each eye a *distance of most distinct vision,* normally about 12 inches.

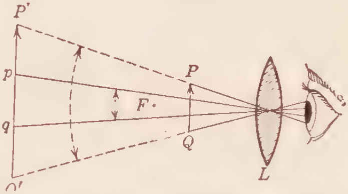


Fig. 334. The Simple Microscope

To examine an object at less than this distance, we view it through a converging lens (Fig. 334), which forms an enlarged upright image at a distance at which the eye can see it distinctly. To get such an image, the object must be at less than the focal distance from the lens (Fig. 307). The best position is when the image is at the distance of most distinct vision, but, since the image can be seen when it is at any greater distance, the position of the object can be varied considerably. The magnification is the ratio of the visual angle of the image *P′Q′* to that of the object *PQ*, when the object is placed at the distance of distinct vision.

Why do we see a near-by object more clearly than a distant one? What is the distance of most distinct vision for the normal eye? What is a simple microscope? What kind of image does it produce? Why does it make an object appear larger?

359. The Compound Microscope.—In the compound microscope two lenses mounted in a tube are used to produce two magnifications (Fig. 335).

One lens *L*, called the **objective,** forms an enlarged, *real* image, *A′B′*, of an object, *AB*, that is placed close outside the principal focus. This magnification is the ratio of *A′B′* to *AB*, and is, therefore, greater the closer *AB* is to the principal focus. The **eyepiece** *L′* is a simple microscope and forms an enlarged, *virtual* image, *A″B″*, just as if *A′B′* were a real object. The ratio of the length of *A″B″* to that of *AB* is the power of the microscope. It is usually stated as being so many diameters (*AB* being regarded as the diameter of a circular object).

In a modern high-power microscope the objective is a group of lenses. The one nearest to the object is very thick and of very short focus, in order to give great magnification and to gather in a large amount of light from the object. But it causes distortion and dispersion, and the others in the group are carefully designed so as to neutralize these effects. A drop of oil, of the same refractive index as the thick lens, placed between it and the object (oil immersion objective), makes the image sharper. The eyepiece is an achromatic lens (§ 341). There are also screws for focusing and adjusting, clamps for holding the object, and a mirror for concentrating light on the object.

How many lenses are used in a compound microscope? What is the objective? What does it do? What is the eyepiece? What does it do? What kind of image does each produce? What two factors determine the magnifying power of the microscope?

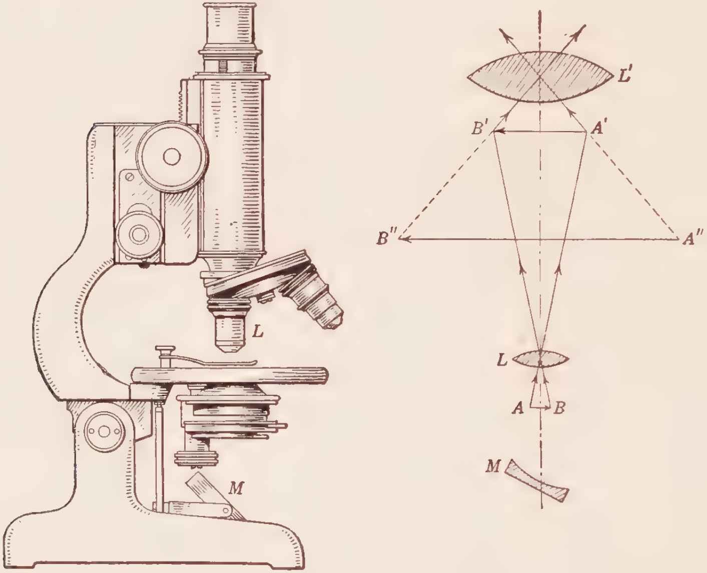


Fig. 335. The Compound Microscope

360. The Telescope.—In the telescope, one lens, called the **object glass,** forms a real image of a distant object and this is magnified by a second lens, the **eyepiece** (Fig. 336*a*). For astronomical purposes, object glasses are of great focal length, so as to form large images, and of great width, so as to admit a large amount of light. In the Yerkes telescope the object glass is 40 inches in width, and of 78 feet focal length. The eyepiece of a telescope is an achromatic lens for magnifying the image formed by the object glass.

The objective forms a diminished real image of a distant object, but the image is close at hand and can be observed under a large visual angle. In a large telescope, like the Yerkes, the magnifying power may be as great as 5000, that is, a planet or part of the moon, as seen in the telescope, seems 5000 times larger than when viewed by the unaided eye.

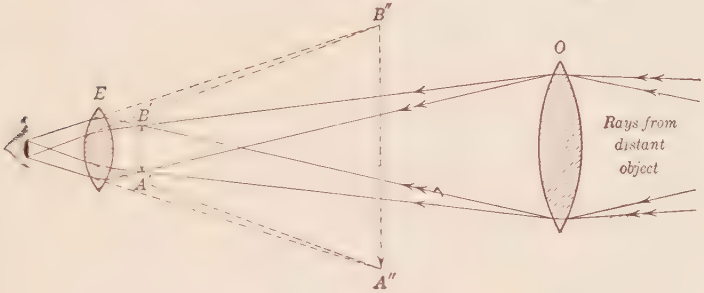


FIG. 336*a*. Astronomical Telescope

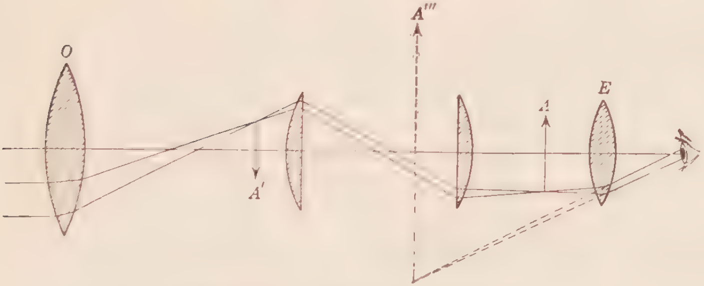


FIG. 336*b*. Terrestrial Telescope

The image in an astronomical telescope is inverted. In small telescopes for terrestrial uses, another lens (or a pair of lenses) is placed between the object glass and the eyepiece to reinvert the image (Fig. 336b). Reflecting telescopes have been referred to earlier.

What is the purpose of the object glass in a telescope? Why is it made of great focal length? Why is it large? What determines the magnifying power of the telescope? How does a terrestrial telescope differ from an astronomical?

361. Opera Glasses.—An opera glass (Fig. 337) consists of a pair of very short telescopes for the two eyes. One device for reducing the length is a concave eyepiece, on which the convergent rays from the object glass fall before reaching a focus. This was in fact the first form of telescope (invented by Lippershey in 1608). The concave lens makes the light divergent (or parallel) and the eye receiving it sees an upright image of the object.

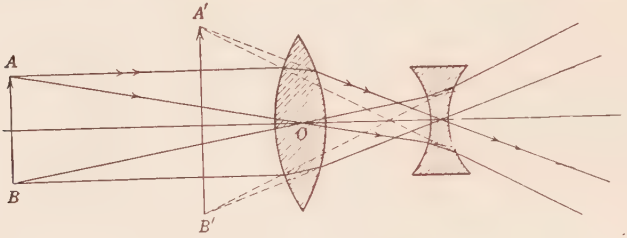


FIG. 337. The Opera Glass

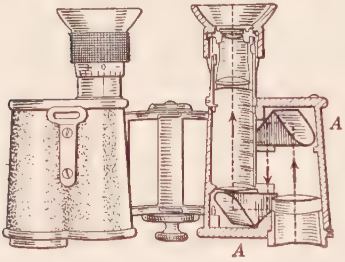


FIG. 338. Prism Binocular

A second device for compactness is to reflect the rays twice inside each tube by two right-angled prisms (Fig. 338), so that they traverse part of the tube three times. In this way object glasses of greater focal length and magnification can be used. Such glasses are called *prismatic binoculars.*

Why is a concave eyepiece used in an opera glass? What is a prismatic binocular? What advantage has it over an ordinary opera glass? What kind of prisms are used in it?

362. Motion Pictures.—When a disk painted with two colors (§ 344) revolves ten or more times per second, the colors combine. This shows that the impression of a flash of light on the eye persists for about one-tenth of a second after the end of the flash. The film of a motion picture machine bears a series of pictures of moving objects, taken at the rate of sixteen or more per second. These are projected on the screen at the same rate. The impression of each lasts until it is replaced by the next, and the eye seems to see a continuous motion. The film has to be at rest for a moment, when a picture is taken and when it is projected. Hence the film in both cases is moved in a succession of jerks. (Fig. 339.)

Special films, called *phonofilms*, now reproduce speech and music along with action. The devices used will be understood better after you have studied electric currents.

How long does an impression last on the eye after the cause is removed? How can this be easily shown? How does this fact make possible the projection of motion pictures? Does the film move steadily? Are the pictures "moving" pictures?

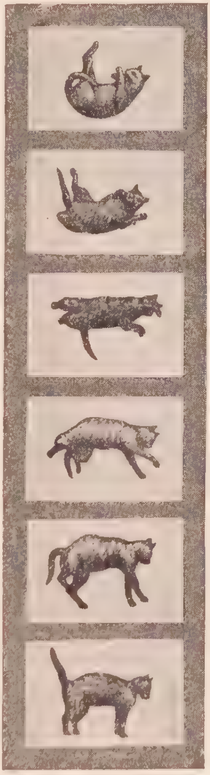


FIG. 339. How a Cat Falls on Its Feet

363. Motion Pictures in Color.—If a motion camera is used to photograph a view, first through a red colored filter, then through a green colored one, and so on alternately, the film, when developed, consists of a series of negatives that record alternately the intensities of the red and green colors of the original. From this negative a positive is printed and projected as usual, except that a rotating disk, half of which is red and half green, is placed in front of the lens. Pictures of the view in green are shown through the green part, and pictures in red through the red part alternately, and the colors follow each other so rapidly that the eye sees them in combination on the screen. As only two of the three primary colors are used, the effect is not a perfect reproduction of the view, and the colors are somewhat unnatural. The effect is improved somewhat by filters that do not exactly reproduce the true primaries.

Some colored motion pictures are produced by using all three of the primary colors, and the results are much better. They are, however, difficult to produce and to project, and are not often shown.

How are films prepared for colored motion pictures? How are the pictures projected? Why are the results imperfect? How may they be improved?

EXERCISES

1. What kind of lens is needed as the projecting lens in a projecting lantern? As the condensing lens?

2. An airplane is flying from west to east. In what direction does its image seen in a camera obscura move? Compare the speeds of the two motions.

3. Why is a single convex lens not suitable for a camera? What kind of lens is required?

4. Why are diaphragms used in cameras? Compare the diaphragms needed for a long and for a short exposure, the object and the camera being the same.

5. What type of lens is the crystalline lens of the eye?

6. What points of resemblance are there between the eye and a camera? What points of difference?

7. Is the image formed on the retina real or virtual? Erect or inverted? Can you explain why we see objects right side up?

8. How does the motion picture operator arrange to show his pictures right side up?

9. A "pinhole" would be cheaper than a lens for a camera. Why is it not more used?

10. Why are snapshots taken under trees usually underexposed?

11. What kinds of lenses are needed for short-sighted people? For long-sighted?

12. Why are powerful astronomical telescopes made very long? Very wide?

13. At first, when coming from a dark room into bright sunlight, it is difficult to see distinctly. Why?

14. What is the relation, with regard to size and distance, between object and image in (a) a photographic camera, (b) a stereopticon?

15. Show by a diagram how an ordinary camera with a short bellows could be used as an enlarging camera.

16. Why do wheels of vehicles sometimes seem to rotate backward in motion pictures?

17. What advantage is there in using concave eye-pieces in opera glasses?

18. What is a prismatic binocular and what is its advantage?

19. What is a telephoto lens and why are such lenses used?

CHAPTER XXXVIII

MAGNETS AND MAGNETIC SUBSTANCES

364. Natural and Artificial Magnets.—Iron has a remarkable property called magnetism that makes it useful in a great many important machines and devices. While most of these practical uses of the property have been found within the last century, the property itself was known in very ancient times.

Many specimens of a mineral called magnetite, a compound of oxygen and iron (Fe_3O_4), attract small pieces of iron. The Greeks called these stones *magnets* from the place, Magnesia, where they were found. An old name for them in English is *lodestone,* but they are more commonly called *natural magnets.* Magnetite is found in many places: at Kursk in Russia there is a deposit of it that covers hundreds of square miles (Fig. 340).

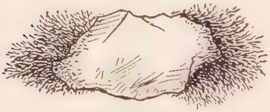


Fig. 340. A Natural Magnet

A piece of hard steel when rubbed on a natural magnet becomes an artificial magnet, or is magnetized. It is then able to attract iron and can be used to magnetize other pieces of steel. Iron can also be magnetized by means of a current of electricity in a way that we shall consider later.

Since natural magnets are now rarely used, the word magnet usually means an artificially magnetized piece of iron or steel.

What is magnetite? Why is it so called? What was the origin of the name magnet? What property distinguishes a magnet from other objects? How may a piece of steel be made a magnet?

365. Induced Magnetism.—A second important fact regarding magnetism was known in ancient times. A nail or any piece of soft iron or soft steel will hang from a magnet (Fig. 341) and, for the time being, becomes itself a magnet, since iron filings will cling to its lower end. Most of the filings drop off when the nail is removed from the magnet, showing that the nail has ceased to be a magnet. Contact between the magnet and the nail is not necessary, for placing a piece of tissue paper between them does not much affect the result. A string of nails may be supported from a magnet, each being temporarily a magnet and making the next a magnet (Fig. 342).

Magnetism that is due to nearness to a magnet is called *induced magnetism.* While it is only temporary in soft iron, hard iron has greater *retentivity,* or power of retaining magnetism. A steel knitting needle or a wire of steel can be permanently magnetized especially if it has been hardened by being heated and plunged into cold water.

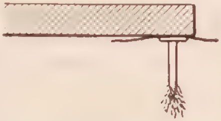


FIG. 341.

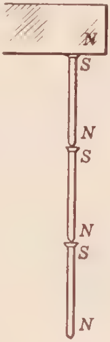


FIG. 342.
The Nails Become Magnets by Induction

What happens to a nail if it is suspended from a magnet? If it is taken away? What is induced magnetism? Which retains its magnetic property better, soft iron or hard iron? How may a piece of soft steel be hardened?

366. Other Magnetic Substances.—Cobalt and nickel have the same kind of magnetic properties as iron, but in a much smaller degree, while many other elementary substances are very slightly magnetic. Manganese is itself feebly magnetic, but certain alloys of manganese are almost as magnetic as iron. This indicates that magnetism is a property of the molecules or atoms of a substance.

What other substances besides iron can be magnetized? How does their magnetism compare with that of iron? Is magnetism a property of atoms or of molecules? Give proof.

367. Poles and Axis of a Magnet.—When a magnet is dipped into iron filings, the filings cling more abundantly to certain parts than to others (Fig. 343). These parts are called the *poles* of the magnet. An ordinary bar magnet has two poles, one at or near each end. The line joining them is called the *axis* of the magnet. A long magnet sometimes has extra poles, or *consequent poles* as they are called (Fig. 344). For example, when the temper is taken out of the middle part of a hard iron wire by heating, it can be magnetized so as to have four poles. It is then in reality two magnets joined by soft iron.

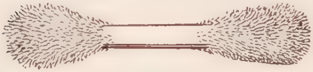


Fig. 343. Poles of a Magnet

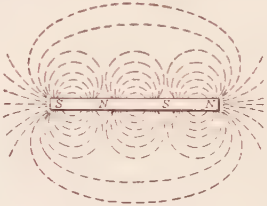


Fig. 344. Consequent Poles of a Magnet

What are the poles of a magnet? What is the least number a magnet may have? In an iron bar where are the poles most likely to be? What is the axis of the magnet? What are consequent poles? How may a magnet be given consequent poles?

368. The Magnetic Compass.—For many centuries the magnet was merely an interesting curiosity, but about 1200 A.D. it was found to have a very important property. When free to rotate horizontally, a magnet will turn nearly north and south. The pole that points north is called a *north pole,* and the other a *south pole.* The earliest mariner's compass was a magnetized needle, attached to a stick or straw floating on water, or placed on a pivot. The modern *mariner's compass* (Fig. 345) is a number of parallel magnetized needles fastened to a card, on which degrees and "points" are marked, a "point" being one-eighth of a right angle. The card is supported on a pivot. In a surveyor's compass the card is fixed, and the needles rotate above it.

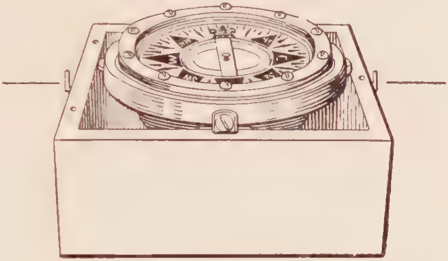


Fig. 345. A Mariner's Compass

The iron and steel of a ship affect the ship's compass, thus introducing errors. These errors are ascertained in advance by comparing the compass readings with known directions, the operation being called "swinging ship." The errors are then compensated by small magnets and bars of soft iron, placed near the compass. The errors of airplane compasses, due to the engine, are found by turning the airplane in various directions on the ground. An allowance for the errors found is made when the airplane is in the air, but in rapid maneuvers the action of the compass is erratic.

How does a magnet behave when freely suspended? When was this discovered? Define north pole of a magnet. South pole. What use is made of this property of a magnet? Describe the mariner's compass. How does the surveyor's compass differ from the mariner's? Why are compasses somewhat unreliable on steel ships? What is meant by swinging ship? What difficulty is experienced with the compass on an airplane?

369. Forces Between Poles.—Another important property of the magnet was discovered by Peregrinus, a soldier, who wrote his account of it while in the trenches at the siege of an Italian city (1269). If a pole of a magnet is brought near the pole of a suspended magnet (Fig. 346), they will repel each other if both are north poles or both south poles, and they will attract each other if one is a north pole and the other a south pole. Hence: **two like poles repel each other, two unlike poles attract each other.**

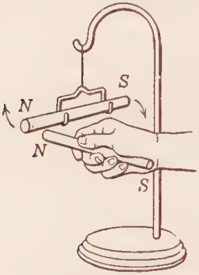


Fig. 346. Like Poles Repel; Unlike Poles Attract

When two like poles are brought very close together, attraction sometimes takes place. This is because the weaker magnet is acted on inductively by the stronger, and has its magnetism reversed.

When a magnetic needle is suspended by a fine wire and a pole of a magnet is brought near one pole of the needle, the needle rotates until the reaction of the twisted wire brings it to rest. The amount of twist of the wire is a measure of the force exerted. By this method Coulomb (Fig. 347) studied the forces between the poles, and found that they followed a law similar to that of gravitation, namely, that **the force between two magnetic poles is inversely proportional to the square of the distance between them.**

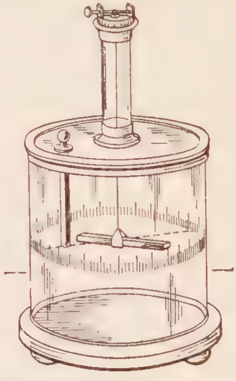


Fig. 347. Coulomb's Magnetometer

How do magnetic poles affect each other? State the law of attraction and repulsion. How may the force of attraction or repulsion be measured? How does increasing the distance between the poles affect the force? State the law governing this force.

370. Magnetic Particles.—The world's knowledge of magnetism before 1600 A.D. consisted of a few disconnected facts. In that year William Gilbert published a book, *De Magnete,* which laid a scientific foundation for the subject. Gilbert found that, when a magnet is broken, two complete magnets result, two new poles appearing at the fracture. The same thing happens when the parts are again broken, and so on, no matter how far we may carry the subdivision. There is reason to believe that very minute particles of the body consisting of a very few molecules forming a tiny crystal are magnetic. This is called the *molecular theory of magnetism.* Why each such particle is a magnet is not yet fully known.

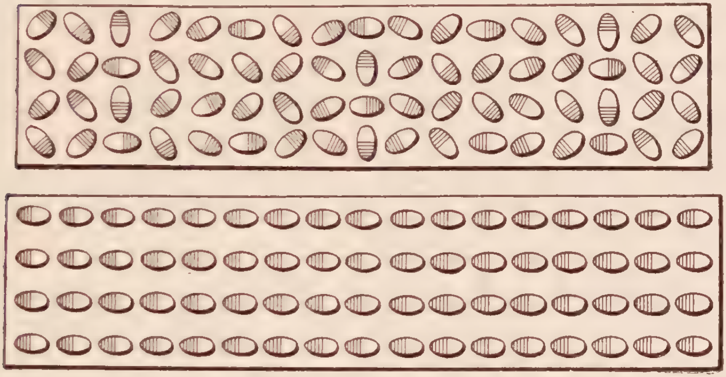


Fig. 348. Molecular Theory of Magnetism

We can now explain what takes place when a rod of steel is magnetized. The tiny magnets in the unmagnetized rod are like a lot of small magnets thrown into a box, their axes being turned in all directions. In magnetizing the rod, we twist these small magnets around, so that their axes are all more or less parallel to the length of the rod. The more completely they are lined up in this direction, the stronger is the resulting magnet (Fig. 348).

The process can be imitated by using a glass tube filled with steel filings. When tested by a suspended needle, the tube is not a magnet, but after it has been rubbed by a magnet it becomes a magnet. When shaken up, it is again neutral, because the arrangement of the particles has been disturbed.

It is found that there is a limit to the strength to which a rod can be magnetized. By using stronger and stronger inducing magnets a time comes when the rod cannot be further magnetized. It is then said to be *saturated.* At this stage all the magnetic particles agree in direction, and since nothing can improve the alignment, nothing can increase the magnetism.

Who was the first to gather together the known facts regarding magnetism? When was the book printed? What is the result of breaking a magnet into two pieces? If these are still further broken, what do you have? What does this indicate regarding the real seat of the magnetism? How does a steel bar which is magnetized differ from one which is unmagnetized? What determines the strength of the magnet? What is a saturated magnet? Why is it saturated?

371. Effect of Heating and of Hammering on Magnetism.

—Many of the properties of magnetic substances are clearly explained by the molecular theory.

If a short rod of hard iron is brought near a magnet and then removed, it may be found to be slightly magnetized. If it is hammered when near the magnet, it becomes strongly magnetized. Hammering agitates the particles and sets them free to turn as the magnet directs them. Twisting, bending, or any kind of straining, produces a similar effect. Hammering, bending, or twisting a permanent magnet weakens it, because it disturbs the particles of the magnet and throws them out of line.

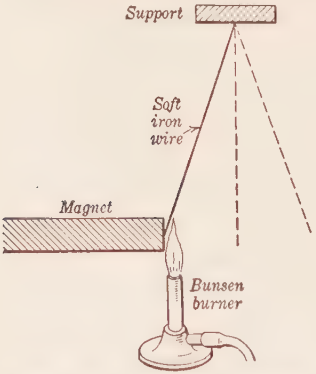


Fig. 349. Heating Destroys Magnetism

A magnetized piece of watch spring will pick up iron filings, but after it has been heated to a red heat, and has cooled, it will be found to be demagnetized. Heat is itself a molecular disturbance, and tends to destroy the alignment of the molecules. For the same reason, soft iron cannot be magnetized by induction if it is at a red heat. A wire of soft iron, mounted to swing as shown in figure 349, will cling to the pole of a magnet, but it loses its hold when heated by a Bunsen burner. When out of the flame, it again becomes magnetic and returns to the magnet, and so it continues to vibrate.

What happens to a piece of hard iron if held near a magnet and hammered? Why? What effect is produced when a magnet is jarred or dropped? Why? How may a magnet be demagnetized? Why does heat produce this effect? Can a piece of hot steel be picked up by a magnet? Explain.

EXERCISES

1. What is a "natural magnet"? How does the property called magnetism manifest itself?

2. What is an induced magnet? Is induced magnetism temporary or permanent? What characteristic of the magnetized metal controls its retentivity?

3. What are the poles of a magnet? How can their position be determined? Why does the existence of a north pole necessitate the existence of a south pole?

4. Given a magnet and a piece of steel rod, just what steps would you take to determine whether the steel is magnetized?

5. Given a magnet and a steel knitting needle, one end of which is marked, how could you magnetize the needle so that the marked end would be a north pole? How could you prove that you had made it a north pole?

6. Given a magnet and a bar of soft iron, how could you tell which was the magnet?

7. Why does heating a magnet destroy its magnetism?

8. Under what conditions will hammering: (a) help magnetization, (b) destroy it?

9. State the facts which in your opinion help to justify our theory of magnetism.

10. A soft iron ball placed a half inch from a magnet was attracted so strongly that it rolled into contact with the magnet. A hardened steel ball of the same size, placed the same distance from the magnet, was seemingly not attracted. Explain why.

11. Why should drawing the temper of the middle of a magnetized bar tend to produce two poles at the softened area?

12. What is the law of force between magnetic poles?

13. How would you prove experimentally that "like poles repel"?

14. Two bars of soft iron are hung vertically, close together, by long threads. On placing a strong magnet close to their lower ends, the bars separate. Why?

15. A nail clings to the under side of the north pole of a magnet. If a second magnet is placed over the first, so that its south pole is over the north pole of the first magnet, the nail will drop. Explain why.

16. Draw a diagram to show your idea of the magnetic molecular arrangement in a magnet, and also in a piece of soft iron.

17. It has been proposed to lift sunken iron ships by dropping huge magnets attached to chains onto the deck of the ship and then lifting it by the magnets. What do you think of the scheme?

18. Why are horseshoe magnets more used than bar magnets? What is the advantage of the soft iron "keeper" or "armature" placed over the poles?

19. How would you prove that the attraction between a magnet and a piece of soft iron was mutual?

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CHAPTER XXXIX

MAGNETIC FIELDS

372. Lines of Force.—A magnet exerts force on the poles of other magnets in its neighborhood. We describe this by saying that it has a *field of magnetic force*, or a *magnetic field.*

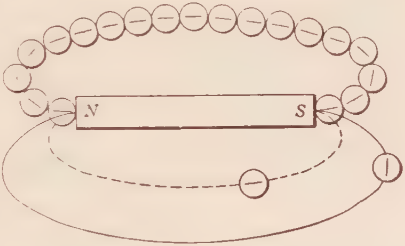

Fig. 350*a*.

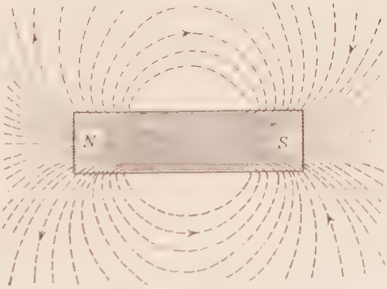

Fig. 350*b*.
Magnetic Lines of Force

The field of a magnet placed on a sheet of paper can be plotted by a short compass needle. For definiteness, let us call the direction from the center of the needle to its north pole the positive direction of the needle. This is evidently the direction in which its north pole is urged by the field. When the needle is near the north pole of the magnet, it points away from the magnet. Let us now move it along, step by step, always in the direction indicated by its north pole, and mark its direction in each position. It will finally come to the south pole of the magnet. The curved line thus traced is called a *line of force* of the field. The positive direction of the line at any point is the direction of the needle when at that point. Other lines of force can be traced by starting the needle at other points near the north pole of the magnet. We may therefore suppose the whole field to be mapped out by such lines (Fig. 350).

The strength or *intensity* of the field is different at different points, as indicated by the rapidity of the vibrations of the needle before it comes to rest. Near the poles of the magnet, where the needle vibrates rapidly, the field is strong, at a distance from them it is weak.

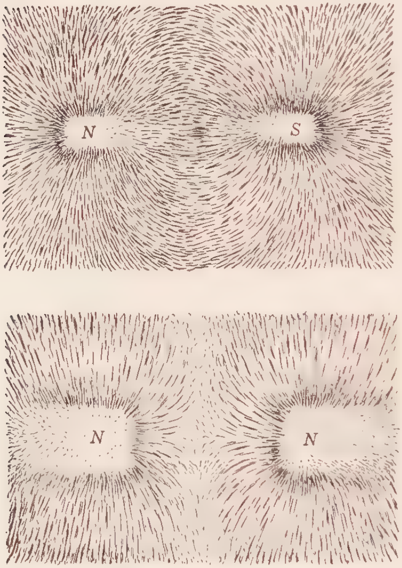

Fig. 351. Mapping the Magnetic Field

What is meant by the field of a magnet? How may this field be made evident by means of a compass? Define line of magnetic force. Where does it begin and where does it end? How may a compass be used to show the relative strength of different parts of the field?

373. Mapping a Field by Iron Filings.—The lines of force in a magnetic field can be shown by a more rapid method. Place a sheet of cardboard over a magnet or group of magnets. Shake iron filings evenly over the card and tap it lightly. The filings will link together along the lines of force. Each particle becomes a magnet *by induction*, and its axis, like that of the small compass needle, turns in the direction of the line of force through its center. Where the filings are numerous, each is in contact with its two neighbors on the same line, and the line is continuous. The lines crowd together where the field is strong, and spread apart where it is weak (Fig. 351).

While the lines thus mapped by iron filings coincide with the lines of force of the field, a line through each chain of filings is more properly a *line of induction* in iron. We might suppose any part of such a continuous chain to be a strip of iron. Hence we see that when iron is placed in a magnetized field it is traversed by lines of induction.

Figure 352 shows the result of placing a block of iron in the field. Near it the lines of force crowd together and pass through the iron as lines of induction. This is described by saying that iron is more permeable to the lines of a field, or, its *permeability* is higher than that of air. A watch is often protected from magnetism by enclosing it in a soft iron case, which serves as a *shield*. The magnetic lines curve around, keeping in the iron and leaving the space inside the case nearly free from magnetic forces.

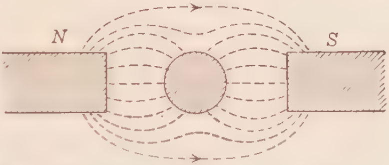

FIG. 352. Permeability of Soft Iron

The device of lines of force for representing magnetic fields was introduced, a century ago, by Michael Faraday. He was a pioneer in the modern study of magnetism and electricity, and when he began his important studies, he was not satisfied with mere laws of attractions and repulsions and formulas for calculating these forces. He sought to understand the underlying causes of the actions that take place, for this is the real aim of the physicist. For example, Faraday noted that the lines between two *opposite* poles (Fig. 351) looked as if they were in a state of tension, like elastic bands stretched between the two poles. He regarded these as real states of strain of the medium between the two poles, and we see that this would account for the tendency of the two poles to draw together or attract each other. But why, then, do the lines not shrink to straight lines connecting the two poles? It looks as if the lines also repelled each other. This is seen also in figure 351, where the lines from the two *like* poles seem to be repelling one another, and this repulsion of the lines would account for the repulsion of the poles to which they are attached. Later we shall see that Faraday's device of lines of force for representing magnetic fields has been found of the greatest importance in devising practical applications of electricity and magnetism.

How may iron filings be used to show the field? How is the relative strength of different parts of the field shown? What is a line of induction? What effect is produced by placing a block of soft iron in the field? Define permeability. Why does a soft iron case protect the works of a watch from a magnetic field?

EXERCISES

1. What is a magnetic field? What are lines of force? Which is the positive direction along a line of force?

2. How would you examine a place to find whether there is a magnetic field there?

3. Explain why an iron filing lines up along a line of force.

4. If you have mapped out a magnetic field by means of a magnetic needle, how would you tell by inspection whether the field is stronger at one given point than at another?

5. How do the vibrations of a magnetic needle change when it is taken from a weak part of a field to a strong part?

6. How does the existence of lines of force help us to explain why a north pole attracts a south pole?

7. How could you best protect a watch from magnetization? Draw a diagram explaining how the scheme works.

8. How would a compass behave if enclosed entirely in a glass box? If placed in an iron box?

9. Sketch the magnetic field in each of the cases below.

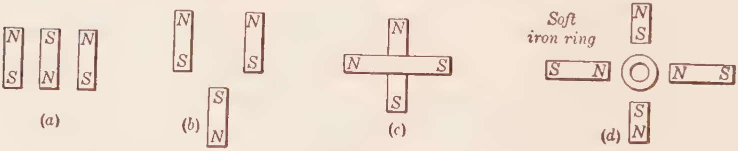

FIG. 353.

CHAPTER XL

THE EARTH'S MAGNETISM

374. The Magnetic Declination.—The discovery that a compass needle does not point exactly north was made by Columbus in 1492, and almost led to a mutiny on board his ship, as it seemed to render the compass unreliable.

The angle between the direction of the compass needle and the true north is called the *magnetic declination* (or the "variation," as surveyors call it). This declination varies over different parts of the earth, and, in fact, is not constant at any one place, but the change is only a small fraction of a degree in a year. At present on the northeastern coast of the United States the compass points west of north, while on the western coast it points east of north.

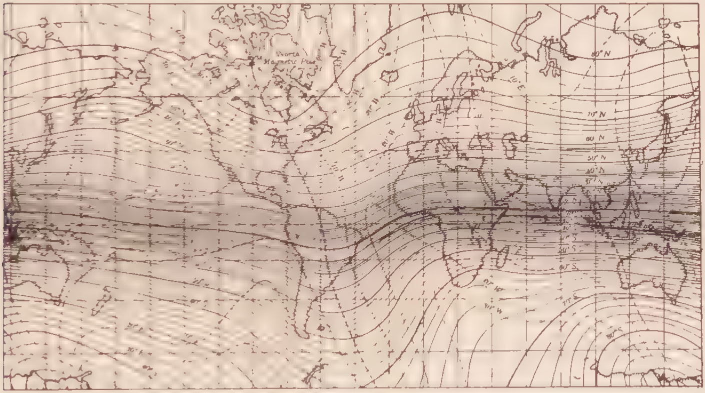

Fig. 354. Magnetic Map

On magnetic maps (Fig. 354) *isogonic lines* are drawn through points of equal declination. The *agonic line* passes through points of zero declination. East of this line the compass points west of north, while west of it the declination is toward the east.

Does a compass needle point directly north? Who first noted this fact? Define magnetic declination. What other term is sometimes used? Is the declination the same in all parts of the earth? How does it vary? What importance has this variation? In which direction is the declination in Boston? In San Francisco? Define isogonic lines. Define agonic line. Determine from the map where the agonic line cuts the United States. How is a knowledge of the declination of use to the mariner?

375. Magnetic Inclination or Dip.—A compass needle is not free to turn in all directions, for it is supported at a point *above* its center of gravity, and it therefore swings in a horizontal plane. It was discovered, in 1576, that a magnetic needle, suspended at its center of gravity, does not remain horizontal. Such a needle is called a *dipping needle,* and the angle it makes with the horizontal is called the *magnetic dip or inclination* (Fig. 355).

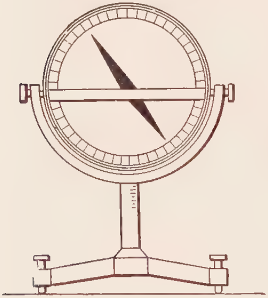
Fig. 355. Dipping Needle

The dip is different in different places and also slowly varies with time. On magnetic maps (Fig. 354) *isoclinic lines* are drawn through points of equal inclinations or dip. The line of zero dip is called the *magnetic equator.*

Define magnetic dip or inclination. How can the dip be shown? Is the dip the same in all parts of the earth? Explain. What are isoclinic lines? Why is one end of a compass needle to be used in New York made heavier than the other? Which is the heavier end?

376. The Earth a Magnet.—Why a compass or dipping needle should point in a definite direction, different at different places, remained a mystery until Gilbert found the explanation. *The earth is itself a magnet* and is therefore surrounded by a field of magnetic force. The force that acts on a compass needle is the horizontal component of the whole force.

A rough idea of the earth's field can be found in the following way. Draw a large circle on a sheet of paper and place a short, powerful magnet at the center, with its axis horizontal. Place a compass needle at various points on the circle, and mark its direction in each position by an arrow. Remove the magnet and fasten the sheet on the wall. The angle between an arrow and the circle represents the dip at a point on the earth's surface. By imagining the circle to be rotated about the line *N.P.-S.P.* as an axis, we can form an idea of the earth's field at its surface. (Fig. 357.)

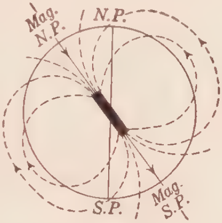

FIG. 356. Earth's Field

The earth can be used as a magnet to magnetize by induction. A steel rod, pointed in the direction of the dip and hammered, will become a magnet, but it will lose its magnetism when pointed east and west and hammered again. Iron fence poles and the steel plungers of elevators become magnets. Hard iron and steel in ships are magnetized by the hammering in the building of the hull. The magnetization of the hull of a battleship in action is continually being changed by the shock of the discharge of big guns. The magnetic compass is then useless, and a different instrument, called the *gyroscopic compass*, which depends on the rotation of the earth, is used. The latter is used exclusively in submarines, because the iron hull shields the interior from the earth's magnetic field, so that the magnetic compass would be useless there.

Why does the compass point toward the north? Prove that the earth has a field of magnetic force? How can this field be used to magnetize a piece of iron? Why are steel towers of bridges always magnets? Why is a compass particularly unreliable on a battleship? What is used to supplement the magnetic compass? Upon what does the gyroscopic compass depend for its directive force? Why is it especially valuable in submarines?

377. Magnetic Poles of the Earth.—There are two places on the earth's surface where the dip is 90° (Fig. 357). One of these in the extreme north of America is the northern magnetic pole. The other almost opposite to it, in the southern hemisphere, is the southern magnetic pole. Neither is near a geographical pole, and both are very slowly changing their position. Amundsen reached the northern magnetic pole in 1905. It is in longitude 96° 43′ west and latitude 73° 31′ north, or about 1400 miles from the geographical north pole. The southern magnetic pole was found by Shackleton in 1909 to be in latitude 72° 25′ south and longitude 155° 16′ east.

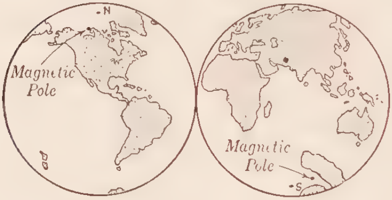

Fig. 357. The Magnetic Poles

If you will locate these two points on a globe, you will see that they are not exactly at the opposite ends of a diameter of the earth.

While the earth is undoubtedly a magnet, how it became so and what keeps it so are wholly unknown. It does not consist of magnetic materials such as magnetite, and it is too hot in the interior to be an induced magnet. Its magnetism is probably due to currents of electricity, but we do not know how they are maintained.

Where are the magnetic poles of the earth? Do we know what causes the earth to be a magnet? What may be the cause?

EXERCISES

1. What is the essential difference between a compass needle and a dipping needle?

2. The locomotives which run through the tunnel of the N. Y. Central R. R. in Manhattan are found to be huge magnets. Can you suggest a likely explanation?

3. Why does the firing of guns on a battleship affect the compass? Which pole of the compass points to the magnetic north pole of the earth? Explain.

4. How do we know that the earth is a magnet? Are there lines of force passing through the air of the street?

5. Since the north magnetic and the north geographical poles are not in the same place, how does it come that the compass is so useful?

6. Why are the isogonic lines irregular? If you stood on the agonic line to which pole would the compass point, the north magnetic or the north geographical?

7. What is the general shape of the isoclinic lines?

8. What would be the position of a dipping needle at the north magnetic pole? At the north geographical pole?

9. The expression "the compass is attracted to the north pole" is sometimes used. If you float a magnetized needle on a cork in a basin of water, will it really move toward the north? Explain.

10. Vertical iron fence posts are frequently magnets. Which end will be the north pole?

11. An explorer recently wrote that he was so close to the north magnetic pole that the compass was useless. Explain.

CHAPTER XLI

CHARGES OF ELECTRICITY

378. Electrification.—Electricity cannot be seen; yet nearly everyone is now familiar with it as something by means of which street cars and trains can be run, streets and houses can be brightly illuminated, and telegrams and telephone messages can be sent thousands of miles with or without wires. All these uses of electricity were discovered in the last century. They grew out of the study of a curious experiment that had been known since 600 B.C. About that time the Greeks found that amber (the Greek name for which was *electron*) had, when rubbed, the peculiar property of attracting light bodies. We can repeat this experiment by using a stick of sealing wax, a piece of sulphur or resin, or the hard rubber case of a fountain pen. When one of these is rubbed with flannel, it attracts small pieces of paper, feathers, or shreds of cotton wool, brought near it (Fig. 358). Bodies that have acquired this property are said to be **electrified**. The condition can be destroyed at once by rubbing the hand over the electrified substance. The body is then described as **unelectrified** or **neutral**. A sheet of paper, rubbed with flannel, is electrified; when held against a wall, it clings to the wall. Leather belting in cotton factories becomes electrified by running over pulleys, and cotton clings to it. In fact everything can, under suitable conditions, be electrified.

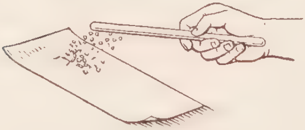

FIG. 358. Friction Generates Electricity

What is the origin of the term electricity? What is an electrified body? How may most bodies be electrified? What is a neutral body? Why does a leather belt often become electrified while running?

379. Charges of Electricity.—A gilded pith ball, hung by a silk thread, is convenient for testing electrified bodies. With it we can perform the following experiment:

1. When sealing wax, electrified by rubbing, is brought near the pith ball, the ball is attracted, touches the wax, and is then repelled and flies off (Fig. 359).

2. When the hand is rubbed over the electrified sealing wax and touched to the ball, both sealing wax and ball become **neutral,** and the hand is also neutral; that is, it does not attract the pith ball.

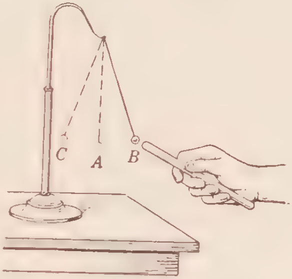

Fig. 359. Pith Ball Electroscope

Similar experiments can be performed with other electrified bodies. We attribute the state of the electrified bodies to something we call **electricity,** and we say that the bodies have received **charges of electricity,** which cause the actions, just as the charge in a gun enables it to produce certain mechanical effects.

In the first experiment, part of the charge of the sealing wax goes to the pith ball on contact between them, and the ball flies away, because the charge on it and that on the wax repel each other.

In the second experiment, the wax and the ball become neutral, because the electricity escapes through the hand to the body and through the body to the earth. The body conducts the charge away and is described as a **conductor of electricity.**

What happens when an electrified sealing wax is brought near a suspended pith ball? After the pith ball touches the wax? How may the sealing wax or the pith ball be made neutral again? Explain the term charge of electricity. Why does the pith ball fly away after it has touched the wax? Why is it made neutral by coming in contact with the hand?

380. Conductors and Non-Conductors.—A charged pith ball can also be discharged by touching it with a rod of any metal, a wet stick, or any one of many other articles. They are therefore *conductors* of electricity. A rod of glass or ebonite or a dry stick will not discharge the pith ball, and such bodies are called *non-conductors.* But no substance is a perfect conductor or a perfect non-conductor.

CONDUCTORS	NON-CONDUCTORS
All metals	Glass
Wet wood	Dry wood
Carbon	Sealing wax
Cotton	Rubber
Flannel	Silk
Earth	Amber
Stones	Porcelain

It will be observed from this list that the bodies that we electrified by rubbing are all non-conductors. When they were held in the hand and electrified by rubbing, the electricity did not escape. A metal rod cannot be electrified when held in the hand; but a metal rod with an insulating handle can be electrified. The list also shows why silk was used to suspend the pith ball.

Non-conductors are also called **insulators**. Wires for electric lighting in houses and for bell circuits are enclosed in a covering of rubber; and telegraph, telephone, and electric light wires out of doors are suspended on glass "insulators" to keep the electricity from escaping to the earth.

Define conductor of electricity. Non-conductor. Mention several conductors and several non-conductors. Can a conductor held in the bare hand be electrified? Explain. What are insulators? Why are most electrical wires insulated?

381. Two Kinds of Electrification.—Another important fact is shown by the following experiments:

1. A pith ball electrified by contact with sealing wax is **repelled** by the sealing wax, but it is **attracted** by a glass rod that has been rubbed with silk (Fig. 360). Conversely, if it is electrified by contact with the rubbed glass, it is repelled by the glass but attracted by the sealing wax.

2. An electrified stick of sealing wax in a stirrup is repelled by another electrified stick of sealing wax, but is attracted by electrified glass.

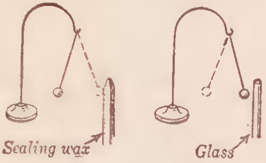

Fig. 360. Like Charges Repel; Unlike Charges Attract

From these experiments we see that there are two kinds of electrification. These are due to **two different kinds of electricity.** The electricity that causes the electrification of glass when rubbed with silk is called **positive** electricity, and that which causes the electrification of sealing-wax rubbed with flannel is called **negative** electricity. These terms were selected at random in the early days of the study; they might just as well have been reversed.

An uncharged or neutral body is one that contains equal amounts of both kinds of electricity. These exactly neutralize each other, just as $+x$ and $-x$ added give zero. A body that has either kind in excess is charged, positively or negatively, according to which kind is in excess.

Two charges of the same kind are called *like* charges, those of opposite kinds *unlike* charges. From the preceding experiments we see that **like kinds of electricity repel each other, unlike kinds attract each other.**

What effect does a rubbed glass rod have on a pith ball which has been in contact with electrified sealing wax? What effect does the sealing wax have on the same pith ball? What does this show about the sealing wax and the glass? What do you conclude from such experiments? What names are applied to the two kinds of electricity? When is a body neutral? Positive? Negative? What is the law of attraction and repulsion of electrical charges?

382. The Gold Leaf Electroscope.—A very convenient device for testing charges (Fig. 361) consists of two strips of gold leaf suspended from a metal rod, which passes through a stopper in a glass flask, and carries a metal plate or ball on its upper end. When there is a charge on the light metal leaves, they repel each other and spread apart. When an electrified body is rubbed on the plate, the electroscope is charged and the leaves diverge. It can also be charged by rubbing the plate with flannel, a proof that a metal can be electrified by rubbing when it is insulated.

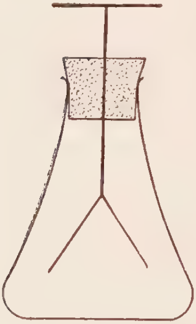

FIG. 361. Gold Leaf Electroscope

Describe the gold leaf electroscope. How does it indicate the presence of a charge? Why do the leaves diverge?

383. Law of Electric Force.—Charges on two small bodies either attract each other or repel each other. The closer they are together the greater is the force of attraction or repulsion. Coulomb measured the force, f, between two small charged bodies suspended in air, and found that it follows a law similar to the law of gravitation, being (a) proportional to the product of the charges q and q', and (b) inversely as the square of their distance, r, apart.

How is the force of attraction or repulsion affected by the distance between the charged bodies? State Coulomb's law for electrical charges.

384. Nature of Electricity.—It was long believed that what we have described as positive and negative electricity were two fluids without weight, which could pass from one body to another. In the last thirty years much has been learned as to the real nature of electricity. Matter contains **electrons,** all of the same size and all negatively charged. An atom consists of a positively charged nucleus or core, surrounded by a number of revolving electrons, like the sun with its revolving planets. **In a non-conductor** the electrons are held firmly by the atoms, and can only be torn away by some effort, as in rubbing. When sealing wax is rubbed with flannel, some electrons, torn from the atoms in the flannel, pass to the sealing wax and are again captured by atoms. *Thus the sealing wax becomes negatively electrified by* **gaining electrons,** *and the flannel positively electrified by* **losing electrons. In a solid conductor** some electrons are loosely held by the atoms. Many escape and travel through the conductor, passing between the atoms, which are much larger, or jumping from atom to atom. Positive electricity does not travel by itself; it stays with the nuclei of the atoms, and travels only when they travel. The smallest charge of positive electricity is that on the nucleus of a hydrogen atom and is called a *proton.* It is equal in magnitude to the charge of an electron.

What was the early belief regarding the two charges of electrictiy? What are electrons? What kind of charge do they seem to consist of? What do we believe to be the structure of the atom? How do the electrons of a non-conductor differ from those of a conductor? How does a body become negatively charged? Positively charged? How do the electrons behave in a solid conductor like a copper wire? How does a positive body differ from a neutral one?

385. Equal and Opposite Charges Produced by Rubbing.—

We cannot produce one kind of electricity without at the same time producing an equal quantity of the other kind. When flannel is used to rub sealing wax, a positive charge is produced on the flannel, but the flannel is a conductor and electrons stream in through the hand and the flannel and neutralize the positive charge. To preserve the charge on the flannel

Fig. 362. Equal and Opposite Charges Produced by Rubbing

we may use a cap of flannel on the end of the stick of sealing wax (Fig. 362), holding the flannel by a silk thread. When the cap is turned several times on the sealing wax and the two in combination are tested by an electrified pith ball, they seem to be unelectrified. But when the cap is drawn off, both it and the sealing wax are found to be electrified. Hence, when together, they must have had equal and opposite charges.

Can one kind of charge be produced without the other? How can you show that both kinds are produced at the same time? Why does the sealing wax with the flannel cap still on it not attract the pith ball?

Fig. 363. Proof Plane

386. A Charge Is All on the Outside of a Conductor.—To test the charge on different parts of a conductor a "proof plane" is convenient. A simple form consists of a cent, fastened by sealing wax to an end of a glass tube, which serves as an insulating handle (Fig. 363). To test an electrified metal cup or a hollow metal sphere which has a small opening (Fig. 364), the proof plane is touched to various points inside and outside, and the charge received by the proof plane is then tested by an electroscope. When this is done, it is found that the inside of the conductor has no charge whatever, the charge being **entirely on the outside.** This might be expected, since the different parts of a charge repel one another.

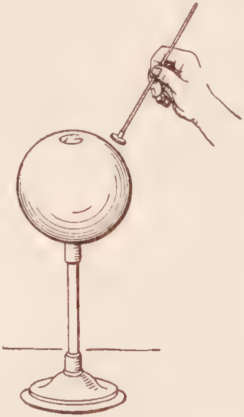

Fig. 364. Charge is on the Outside of a Conductor

What is a proof plane? How is it used? What can be learned with it? Where is the charge on a charged hollow sphere? Why is this so?

387. Distribution of a Charge on a Conductor.—The density of the charge on different parts of the surface of a charged and insulated conductor may be tested by applying a proof plane to different parts, and then testing the plane by an electroscope. When this is done, it is found that the density is greatest on the part of an oval surface (Fig. 365) where the curvature is sharpest, and less where the curvature is less.

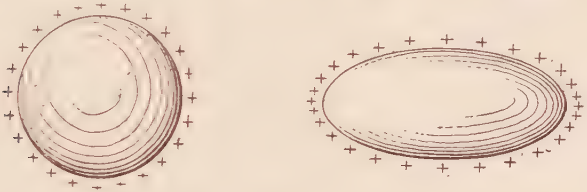
FIG. 365. Distribution of Charge

When an irregular conductor is insulated from surrounding objects and charged, does the charge distribute itself evenly all over it? Where is the charge the densest?

388. Effect of Points on a Conductor.—If a conductor has a pointed end, the density becomes so great at the point that the charge streams off, and the conductor becomes discharged. This may be shown by thrusting a needle through a strip of dry wood, which will serve as an insulating handle, and then

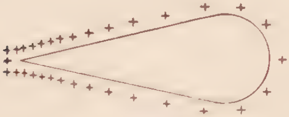
FIG. 366. Effect of Points on Distribution

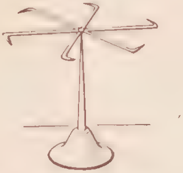
FIG. 367. Electric Wheel

touching the head of the needle to the plate of a charged electroscope. The leaves will slowly collapse, showing that the charge is leaking away from the point of the needle (Fig. 366).

The discharging effect of points is shown by the "electric wheel" (Fig. 367). This consists of a socket mounted on a needle point, with several wires attached radially to the socket. The wires are sharpened at the outer ends, which are bent as shown in the figure. When the needle is connected to an electrical machine, the reaction due to the streaming of electrified air from the points causes a rapid rotation.

All apparatus designed to retain electric charges must be free from points and edges or the electricity will rapidly leak away.

If there is a point on the conductor, what happens? How can this be easily shown? Why does the "electrical wheel" rotate? If an object is to hold its charge, what must be its shape?

EXERCISES

1. What do you mean by an electrified body? What is a charged body? How many kinds of electrification are there? How may they be distinguished from each other?

2. Describe the various ways by which a body may be electrified. How could you electrify a body positively? How could you electrify a body negatively? How would you know that it was negatively electrified?

3. Mention some instances in which electrification occurs in every day life.

4. Can you suggest any explanation of the fact that a piano case becomes dusty so very soon after being cleaned (polished)?

5. Can you explain the fact that it is very dangerous for a woman with long hair to be in the neighborhood of a rapidly moving machine belt? Would loose clothing, ribbons, etc., be dangerous under like conditions? Why?

6. In a certain machine used in the weaving of silk ribbon, the silk threads were fed in by being drawn over a glass roller. The ribbon always looked dirty. Can you suggest a reason and a remedy?

7. Is it possible to electrify all bodies? Can they all be electrified with equal ease? Are there special precautions to be observed with any special class of substances?

8. If you pick up an electrified metal rod, is it discharged? State what happens when you pick up an electrified rubber rod. Explain this in detail

9. What is the electrical state of a suspended pith ball that has just been held in your hand? How would it act toward a positively charged body brought near it (not touching)? How would it act toward a negatively charged body? Explain fully.

10. How would a suspended pith ball hanging from a silk thread behave if approached by a positively charged body which it could touch? Explain fully.

11. If a pith ball suspended by a silk thread is placed between a charged and a neutral body, both of which may be touched by the ball, how will it behave? Why?

12. When a negative charge is produced on a rubber rod by rubbing it with a catskin, what is the electrical condition of the skin? Of the hand which holds it? Is this fur an insulator or a conductor? How do you know?

13. The paragraph on the "Nature of Electricity" should be carefully studied and understood. Write in your own words a description of the process of electrification.

14. What is a proof plane? What are its essential parts? How and for what is it used?

15. Draw diagrams showing the distribution of a charge on: (a) a sphere, (b) an egg shaped conductor, (c) a disk, (d) a cylinder with one end drawn out to a point. All four objects are of metal.

16. An insulated metal coffee pot is positively electrified. A proof plane is touched to various parts of the pot. Which parts will give the most, and which the least charge to the plane? Explain your answer fully.

CHAPTER XLII

INDUCED CHARGES

389. Charging by Induction.—Conductors can also be electrified by a process called **induction,** which is similar to the process of magnetization by induction (§ 365). We shall explain the process as applied to electrifying the gold leaf electroscope by induction, but it will seem that the same explanation will apply to electrifying any other insulated conductor by induction.

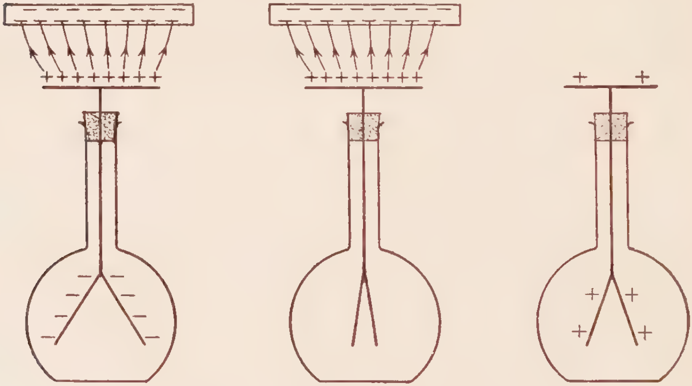

Fig. 368. Charging an Electroscope

If a negatively electrified stick of sealing wax be brought (Fig. 368) above the plate of the electroscope, but without touching it, electrons will be repelled from the plate to the leaves, which will therefore diverge, and the plate will be positively charged. This effect is only temporary, for, as soon as the sealing wax is removed, the leaves collapse, and the metal of the electroscope is left neutral. Now repeat the operations, but making one change. While the sealing wax is present, touch the plate for a moment with a finger. The leaves collapse, showing that their charge of electrons has escaped to earth through the finger. When the sealing wax is removed, the leaves diverge, as the whole electroscope is now deficient in electrons.

The final result is that the electroscope is left positively charged. The same method can be used with the positive charge of a glass rod as inducing charge. The electroscope will then be finally left negatively charged. Evidently the process can be applied to any insulated conductor, with the result that it will be finally left with a charge opposite in sign to the inducing charge.

If a needle, mounted as described in § 388, is held in contact with the electroscope, and a charged rod is brought near the point of the needle, the leaves diverge, and remain diverging when needle and rod are removed. The induced charge drawn to the point of the needle leaks from the point, thus leaving the electroscope charged.

Can bodies be charged without touching them to charged bodies? What is the process called? What happens when an electrified rod is brought near the plate of an electroscope? If the plate be then touched by the finger? If the charged rod be then removed? What kind of charge do the leaves then have? If a body is charged by induction, what kind of charge does it have? If charged by contact, what kind of charge does it have?

390. Use of the Electroscope to Test a Charge.—A charged electroscope is a convenient means of testing the sign of an unknown charge. We first test the action of the electroscope by bringing a known charge, say that on sealing wax, toward the electroscope. The leaves will *begin* either to collapse or to diverge more. If the unknown charge has the same effect it is negative; if it has the opposite effect it is positive. But care must be taken. A charge that will first cause the leaves to collapse may, when brought closer, cause them to diverge again with an opposite charge. An uncharged body when brought toward the electroscope may cause the leaves to collapse partly, but not wholly.

How may a charged electroscope be used to test the kind of charge possessed by another body? What precautions are necessary? If the electroscope is positive and another body be brought near with a further divergence of the leaves, what is the charge of the body?

391. The Electrophorus.—This is a simple device for rapidly producing charges by induction. A *plate* (Fig. 369) of some insulating material, such as sealing wax or sulphur, is electrified by friction, and on it is placed a metal *cover* having an insulating handle. The cover is electrified by induction, and, if the finger be touched to the cover for a moment, the electrons repelled to the top of the cover will escape, and the cover will then have a positive charge. When the cover is raised by means of the insulating handle, it is still charged positively and it can be used to charge another body positively, by contact, or negatively, by induction. The process can be repeated many times without discharging the plate.

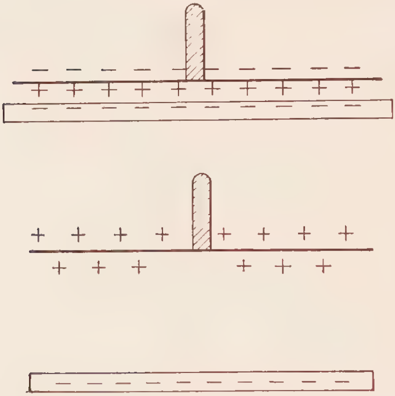

FIG. 369. Charging an Electrophorus

Describe an electrophorus. Diagram the distribution of charges upon the plate and cover when in use. What happens when the finger is touched to the cover? Why? How many times may the cover be charged? If the plate is negative, what kind of charges are obtained on the cover?

392. Potential of a Charged Body.—Various insulated conductors can be charged by rubbing or by induction. When any two of these are touched together, electrons will usually pass in one direction or the other. What property determines the direction in which a charge passes when two conductors are put in contact? Henry Cavendish, one of the greatest discoverers in Electricity, called it the degree of electrification, but for clearness we now call it **electrical potential.**

We say that a body *A* is at a higher potential than a body *B*, if, on connecting the bodies by a wire, electrons would flow from *B* to *A*.

As a zero from which to reckon potential, we take the potential of the earth. The potential of a body is positive, if electrons will flow from the earth to the body when they are connected. If the flow is in the opposite direction, the potential of the body is negative.

What causes electricity to pass from one body to another? Who was Henry Cavendish? Define electric potential. If electricity passes from *C* to *D*, what was the potential of *C* compared with the potential of *D*? What term in heat is analogous to potential? What is the potential of the earth? What must be done to carry positive electricity from a lower potential to a higher one?

393. Electrical Machines.—The principle of induction as used in the electrophorus is also applied in machines for rapidly generating large charges. These machines are complex in details, and of different forms, but they involve no new principle. For a complete account of them, more advanced books should be consulted.

In the Holtz machine (Fig. 370) two large disks of metal, or *inductors*, *I* and *I′* act like the plate of an electrophorus. They are mounted on a large stationary glass plate *P* and are oppositely charged. A ring of small disks, called *carriers*, c_1 and c_2, . . . on a revolving glass plate P', act like the cover of an electrophorus. Two diagonally opposite carriers, while they are in front of the inductors, are touched by brushes on the *diagonal conductor* C, and thus acquire charges, which they carry with them as they move away. Part of the charges they give up, by contact with brushes b and b', to the inductors, and the rest of the charges they carry around to the collecting brushes (or points) B and B', to be carried to the discharging knobs D and D'.

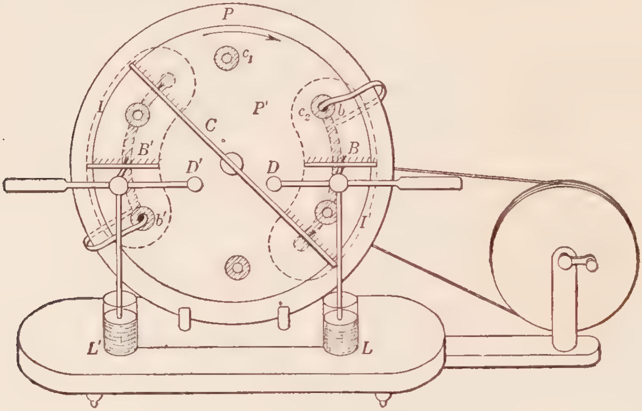

FIG. 370. Holtz Machine

On an electrical machine, what is the purpose of the inductors? Of the carriers? Of the diagonal conductor? What becomes of the charges produced on the carriers? Why can the machine be run indefinitely without loss of charge from the inductors?

394. Lightning.—Franklin showed that a thundercloud is charged with electricity. He sent up a kite, on the top of which there was a pointed wire. The cord by which the kite was flown became a conductor when wet. Electricity was drawn from the wire by the induction of the cloud, and discharges were obtained from the lower end of the cord. The experiment is a dangerous one and should not be tried by any except experts.

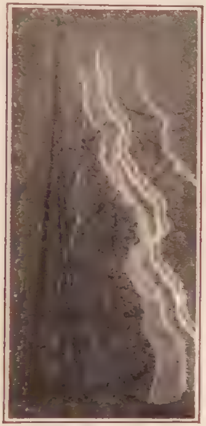

FIG. 371*a*. Ribbon Lightning

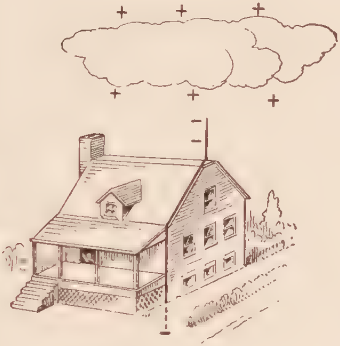

FIG. 371*b*. Action of Lightning Rod

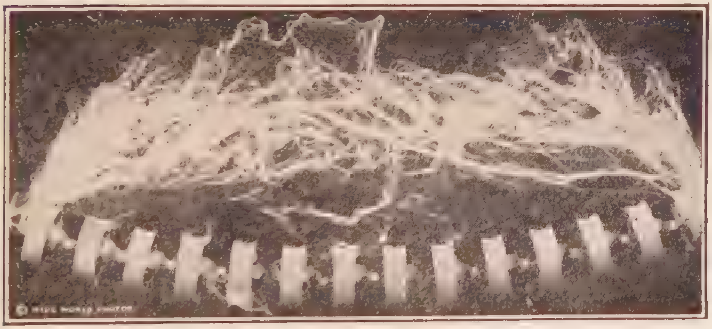

FIG. 371*c*. Man-made Lightning. A million-volt Arc

Franklin also invented the *lightning rod* for protecting buildings from lightning. A wire, with its lower end earthed, runs up the outside of the building, and its upper end extends above the building. The wire either discharges to a passing cloud and so neutralizes the cloud, or it receives the discharge from the cloud, and conducts it harmlessly to the earth (Fig. 371*b*). The conductor should have as few bends in it as possible, or the discharge may take a short cut through the building. If the lower end is not well earthed by a plate in wet soil, the conductor may become a source of danger, for it may draw a charge from a cloud and discharge it to a water pipe in the house. This is why many have lost faith in lightning rods.

Radio antennas which are grounded through the receiving set may become a source of danger during an electrical storm. They should be grounded through a lightning arrester on the exterior of the building.

How did Franklin show that a thunder cloud was charged? How does a lightning rod protect a house? What possible dangers accompany its use?

395. Atmospheric Electricity.—Even in clear weather the air is charged, sometimes positively, sometimes negatively. but the charges are so small that they are not readily detected. The potential of the air is usually positive relatively to the earth, and is greater the greater the elevation. The source of this electricity is still not clearly known.

One manifestation of these atmospheric charges is the *aurora borealis* or "northern lights," consisting of flashing streams of light seen in the northern heavens. The height is usually several miles, but varies widely. The cause of the discharge is not yet definitely known, but it is probably due to a stream of electrons from the sun falling into the earth's atmosphere.

How do you know that the atmosphere is often charged with electricity? Give a suggested explanation of the aurora.

EXERCISES

1. If a wooden rod is suspended horizontally, and a positive charge is brought near one end, the rod turns. Why? If an electrified rod is so suspended, and the hand is brought near, the rod rotates. Why?

2. Sketch, describe, and explain the electroscope.

3. Given a positively charged body. How could you use it to charge an electroscope: (a) negatively, (b) positively?

4. An electroscope is enclosed in a cylinder of fine metal gauze (net), that is grounded. A positively charged body is brought near to it. What happens, and why?

5. Explain the operation of lightning rods. What important precautions are necessary in their installation? Are they ever a source of danger, and under what conditions? Why are trees so often struck?

6. Suggest precautions to be observed when out in a thunder storm. Assume various conditions and suggest the proper action to be taken.

7. If you owned one house of a thousand built on a large flat tract much subjected to thunderstorms, would you install lightning rods? Explain.

8. Explain step by step the process of electrification by contact and by induction.

CHAPTER XLIII

CONDENSERS. CAPACITY

396. Electrical Condensers.—Let two conducting plates *A* and *B* be placed parallel to each other and at a considerable distance apart (Fig. 373*a*). Connect *A* to the earth and *B* to the pole of an electrical machine in action. Then remove these connections, using a glass rod, so that the plates shall not be discharged. On connecting *B* to the earth a spark will take place. Now repeat the experiment with the plates closer together. A larger spark will take place, showing a larger charge on *B*. In a series of such experiments the charge on *B* will be greater *the closer the plates are together.*

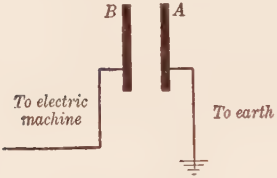

FIG. 373*a*. Action of a Condenser

In these experiments *B* is always raised to the same potential, namely, that of the pole of the machine. But the charge on *B* is increased by the presence of the earth-connected plate *A*. We describe this by saying that the **capacity** of *B* is increased by the effect *A* has on it. The two plates *A* and *B* constitute an **electrical condenser.**

The increase of capacity when *A* is brought closer to *B* is due to the greater attraction which the charge on *A* now exerts on *B*, thus drawing a larger charge from the machine to *B*. Or we may say that *A*, which is always at the potential of the earth, tends to keep the potential of *B* constant. So, to keep *B* at the potential of the pole of the machine, a larger charge must flow to it.

What effect is produced on the capacity of a plate by placing it near another which is earthed? What happens if the plates are brought even nearer together? What is such an arrangement called? What causes the increased capacity?

397. Leyden Jar.—The earliest form of condenser (invented in Leyden) was a glass flask, partly coated inside and outside with tin foil (Fig. 373 *b*), and a metal rod with a ball at the top to make connection with the inner coating. When the outer coating is "earthed" (connected to the earth) and the inner coating is charged by an electrical machine, a large charge can be given to the condenser, and a bright spark is obtained when the inner coating is connected to the outer by discharging tongs. The spark is accompanied by heat and can be used to explode gunpowder or to ignite a few drops of ether or a gas jet. When a jar is discharged through a sheet of cardboard, there is a burr at each end of the perforation, some gas held in the cardboard being forced outward in both directions by the heat of the spark.

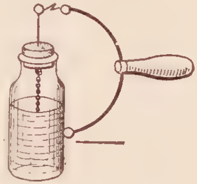
FIG. 373*b*. Leyden Jar

Describe a Leyden jar. How may it be charged? How discharged? How could you show that the discharge is accompanied by heat?

398. Effect of the Medium.—The medium between the plates of a condenser, or the **dielectric** as it is called, plays a much more important part then merely insulating the plates from each other. This is shown by the arrangement in figure 374. *A* is a metal plate mounted on an electroscope, and *B* is a charged and insulated metal plate. The leaves of the electroscope stand apart, owing to induction of *B* on *A*. Now let a plate *C* of insulating material, such as glass or ebonite, be placed between *A* and *B*. The leaves will partly collapse, but when *C* is removed, they will spread apart again.

The dielectric between the plates of a condenser is in a state of strain. If the strain becomes excessive, the material breaks down. The glass of a Leyden jar is frequently punctured by overcharging. A glass plate an inch thick has been ruptured by a very powerful discharge. Hence the insulators for carrying the wires of very high potential transmission lines need to be of very thick and well-annealed glass.

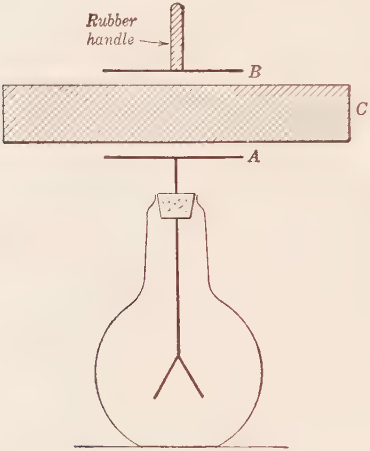

Fig. 374. Effect of the Dielectric

The strain is in the atoms. The electrons in an atom are pulled slightly away from the nucleus by the attraction of the positive plate and the repulsion of the negative plate. There is therefore a stretching of the atom, just as a spring balance is stretched by the attraction of the earth on a body hanging from the balance. When the strain in the atoms becomes too great, the electrons are torn from the atoms and rush to the positive plate causing a spark.

. Define dielectric. What is its importance in a condenser? Can electric attraction and repulsion take place through it? What happens in the dielectric when a condenser is charged? What may happen if the condenser is too highly charged? Why are glass insulators on transmission lines heavy and thick? What is believed to occur in the atoms of the dielectric?

399. Other Condensers.—The capacity of a condenser is proportional to the area of the plates and inversely to the distance between the plates. It also depends on the substance used as dielectric. To form condensers of large capacity, many sheets of tin foil, separated by paraffin wax or mica, are used (Fig. 375). Alternate sheets are connected together in two sets, and these are equivalent to a pair of very large plates very close together. Hence the capacity is large. Condensers are now being extensively used in tuning radio circuits.

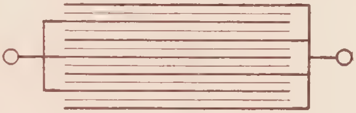

FIG. 375. Plate Condenser

How does the size of the plates influence the capacity of a condenser? Their distance apart? What other factor is important? How are condensers of large capacity constructed?

400. Magnetic Effect of a Discharge.—We have not thus far spoken of any connection between magnetism and electricity. The one we shall now consider was discovered by Oersted in 1820. A discharge of electricity in a wire is a momentary current. Oersted discovered that an electric current acted on a magnetic needle. Suppose, to increase the effect, we wind the wire into a spiral and place a small compass needle near one end. On discharging a large Leyden jar through the spiral, the needle will be disturbed. But the effect is temporary and of the nature of an impulse. The needle, after a few swings following the impulse, settles into its previous position. If the experiment be repeated, but with the discharge in the opposite direction, the first swing of the needle will also be reversed.

What effect does a discharge of electricity through a wire have on a near-by magnetic needle? How may this effect be increased? What does this show?

EXERCISES

1. Given a negatively charged rod, how could you electrify two insulated spheres negatively? How positively?

2. Why do the leaves of an electroscope which has been charged ultimately come together? Why does the speed of this action vary from day to day?

3. Describe the behavior of the leaves of an electroscope at each step of the process of electrification by induction. Explain each change.

4. If a positive charge is brought near a negatively charged electroscope, the leaves collapse. If brought near an uncharged electroscope the leaves diverge. Explain.

5. If an uncharged conductor is brought near a negatively charged electroscope the leaves collapse. Explain.

6. Sketch, describe, and explain the electrophorus.

7. Sketch, describe and explain the condenser. Do you know of any practical use to which condensers are put?

8. Sketch, describe, and explain the Leyden jar. What is the function of the metal coats? Of the glass? What is the molecular condition of the glass when the jar is charged? Have you any evidence to support your answer?

9. Could a Leyden jar be made, having a rubber instead of a glass cup? Explain.

10. Is there any relation between magnetism and electricity? How has it been shown and demonstrated? Has an electric charge at rest any particular influence on a magnet different from that exhibited upon non-magnetic bodies?

CHAPTER XLIV

ELECTRIC CURRENTS

401. The Electric Current.—When the two coatings of a charged Leyden jar are connected by a wire, a momentary discharge takes place through the wire. This is a momentary **current of electricity**. The strain in the dielectric is thereby relieved, and the potentials of the coatings become equal. If, however, the strained condition is kept up in some way, that is, if the coatings are kept at a steady difference of potential while connected by a wire, a continuous current of electricity will flow in the wire. The simplest way of maintaining such a difference of potential is by means of a *primary cell* or *voltaic cell.*

It was formerly supposed that a current of electricity in a wire was a transfer of positive electricity. We now know that it is really a stream of negative electricity, that is, of electrons. Hence the terms that have been used to describe the direction of the current should be reversed. But this change would confuse anyone who tried to read one of the important books written in the old way, and it would therefore be unwise to make the change now. This will not cause you any difficulty in studying electric currents, for you will be concerned only with their effects, and these can be described as well by using the terms in the old way. If positive electricity were free to flow, that is, if it were not immovably connected to atoms, it would move from a place of higher potential to a place of lower potential, just as water flows from a place of high pressure or level to one of lower pressure or level. We shall speak of an electric current as flowing from a place of high potential to a place of lower potential, even though you know that the current in a wire is, in reality, a stream of electrons and that electrons flow from low potential to high potential.

What happens when two coatings of a charged Leyden jar are connected by a wire? What is this discharge called? What is necessary if the current is to be maintained continuously?

402. The Voltaic Cell.—Galvani (a physician of Bologna) described, in 1786, a simple observation that ultimately led to remarkable results. He noticed that the body of a frog which he had dissected, and had hung on a copper hook attached to an iron railing, twitched when one of the legs touched the iron. This resembled the shock of a discharge of electricity, and Galvani believed it was due to electricity in the frog's leg. Volta (of Pavia) doubted Galvani's explanation, and after some experiments he found that, when a strip of zinc and one of copper were partly immersed in dilute sulphuric acid, charges of electricity could be obtained from the exposed ends of the strips. This was the first *voltaic cell.*

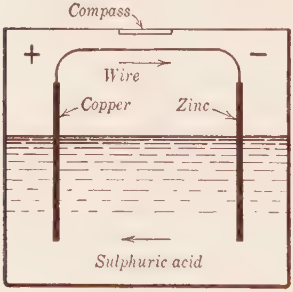

FIG. 376. Simple Voltaic Cell

To show that the voltaic cell produces a current of electricity, let us connect the zinc and copper strips by wires to the spiral used in the experiment of § 400. The needle will now be deflected and the deflection of the needle will be maintained. The direction of the deflection of the needle will be the same as if the copper strip were kept positively charged and the zinc strip negatively charged. The current from a voltaic cell therefore flows from the copper to the zinc in the connecting wire. In the cell it is from the zinc to the copper.* The simple voltaic cell is, however, very imperfect, and the above experiment will succeed better with a commercial type of cell.

What simple observation led to the invention of the voltaic cell? Who made the observation? Why is the cell called a voltaic cell? What did the first voltaic cell consist of? How can you show that a voltaic cell produces a current? Which way does the current flow in the wire connecting the two metals?

403. The Electric Circuit.—The plates in a cell are called its **electrodes.** The liquid is called **the electrolyte.** The entire path of the current, including the external conductor, the electrodes, and the electrolyte, is called **the circuit.** Joining the electrodes by a conductor so that a current can flow is **closing the circuit,** and the cell is said to be **on closed circuit.** Disconnecting the two electrodes is **breaking the circuit** or **opening the circuit,** and the cell is said to be **on open circuit.**

Define: electrode, electrolyte, electric circuit. What is meant by closing a circuit, by opening a circuit? When is a cell said to be on closed circuit?

404. Why a Voltaic Cell Gives a Current.—The study of chemistry has shown that in an electrolyte (a solution of acid, base, or salt) some of the dissolved molecules *dissociate,* that is, break up into parts called **ions.** The metallic part of the compound gives metallic ions, which are always charged *positively.* The non-metallic part forms non-metallic ions, which are always charged *negatively.* The total positive charge is always equal to the total negative charge. Hydrogen is a metallic ion and always carries a positive charge. This is the **dissociation theory.** It explains many facts in chemistry that were formerly puzzling.

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* The student can remember the direction of the current from the word *z-in-c,* meaning from the *zinc in* the liquid to the *copper.*

A molecule of sulphuric acid is composed of two atoms of hydrogen, one atom of sulphur, and four atoms of oxygen. For brevity chemists write it H_2SO_4. When sulphuric acid is dissolved in water, some of the molecules of the acid dissociate, and the solution contains not only molecules of water and of sulphuric acid, but also positively charged hydrogen ions $(H^+ + H^+)$ and negatively charged sulphion ions (SO_4^{--}):

$$H_2SO_4 \longrightarrow H^+ + H^+ + SO_4^{--}$$

One molecule gives positive and negative ions.

When the circuit is closed and a current is flowing, zinc is dissolving, forming positively charged zinc ions Zn^{++}, and leaving a negative charge on the plate. The SO_4^{--} ions travel toward the zinc plate, where they combine with zinc ions, forming zinc sulphate. The hydrogen ions migrate toward the copper plate, where they take in electrons from the copper plate, and unite to form molecules of hydrogen *on the copper plate.* The current produced is equal to the sum of the charges of the electrons taken in per second from the copper plate by the hydrogen ions. In the wire or "external circuit" the flow of electrons is from the zinc to the copper plate, but this we have agreed to call a current from the copper to the zinc.

What happens when an acid, a base, or a salt is dissolved in water? What is meant by dissociation? What are ions? What kind of charge does a metallic ion carry? A non-metallic ion? State the dissociation theory. What ions are present when sulphuric acid is dissolved in water? Which ions move with the current? Which ions move to the copper plate? What happens to them there? What relation exists between the charges on the ions and the strength of the current from the cell?

405. Energy from a Cell.—In the simple voltaic cell the result chemically is that zinc replaces hydrogen in combination with SO_4:

$$Zn + H_2SO_4 \longrightarrow ZnSO_4 + H_2$$

Since the energy of the chemical compound $ZnSO_4$ is less than that of H_2SO_4, chemical energy is used in keeping up the current. Any two conductors immersed in an electrolyte that acts chemically on one of them can form a voltaic cell and give a current, and in all cases chemical energy is used. A voltaic cell is therefore a device for **transforming chemical energy into electrical energy.** In commercial cells zinc is usually the metal consumed, and the amount consumed determines the amount of electrical energy developed, just as the amount of coal burned under a boiler determines the amount of steam developed. *Zinc is the fuel of the voltaic cell.* The reason why such cells are not more used is because the fuel is so expensive.

What is the primary chemical action in the voltaic cell? What is consumed to supply the energy? What energy transformation goes on in the cell? In what way does the zinc resemble a fuel?

406. The Electromotive Force of a Cell.—Any influence that causes a motion of matter we call a force. Any influence that causes a motion of electricity, that is, an electric current, is called an **electromotive force** or **e.m.f.** Thus we speak of the e.m.f. of a cell, of a dynamo, or of any generator of electric currents. The following analogy will help to make the meaning clearer.

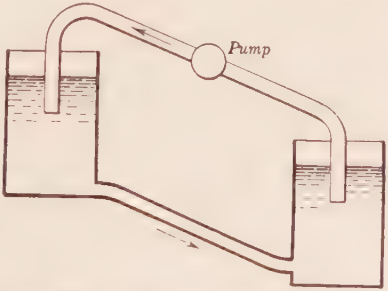


FIG. 377. Hydraulic Analogy of Cell

There is a marked resemblance between the action of a voltaic cell and that of a pump. If a pump be used to raise water from a tank at a low *level* to one at a higher level (Fig. 377), a continual flow of water can be obtained through a return-pipe connecting the two tanks. Similarly the chemical action in a cell raises the *potential* of the copper (carbon) plate above that of the zinc plate, and a continuous current flows through a conducting wire connecting the two. To calculate the flow of water we need to know the force of the pump, that is, the highest level to which it can raise water. This highest level will evidently be obtained when the return-pipe is closed. Similarly, to calculate the current that can be obtained by use of a cell, we need to know the greatest difference of potential it can produce. This maximum difference of potential exists between the plates when there is no current, that is, when the circuit is open. This is called the electromotive force of the cell.

The electromotive force (e.m.f.) of a cell is equal to the difference of potential of the plates when the cell is on open circuit.

The e.m.f. of the cell is not changed by closing the circuit, but the potential difference of the plates falls, just as the difference of level of the two water tanks falls, in spite of the action of the pump, when they are connected by a pipe and a flow is taking place.

What is a force? What is an electromotive force? How is the term abbreviated? What is necessary if water is to flow continually from one tank to another? What similar relation exists in an electric circuit? Which plate in the voltaic cell is at the higher potential? How is it maintained at the higher potential? Define the electromotive force of a cell. Why should you state "on open circuit"? If the current drawn from a cell be increased, what change takes place in the potential difference between the plates?

407. Other Uses of the Term E.M.F.—The term e.m.f. is also applied to a circuit, as when we speak of the e.m.f. in a circuit or around a circuit. When the circuit contains a single cell the e.m.f. in the circuit is simply the e.m.f. of that cell. When several cells are used in combination, the e.m.f.

in the circuit can be calculated from their separate e.m.f.'s, their number, and their arrangement (see §§ 442-443).

When a current is flowing in a wire, at each point the potential has a definite value, just as there are definite pressures at points in a pipe conveying water. The difference of the potentials at two points in the wire may be considered as the cause of the flow in that part of the wire and is often called the e.m.f. in that part. It is better, however, to refer to it simply as the potential-difference between the points.

When a current flows in a wire, are all points in the wire at the same potential? Where is the potential greatest?

408. Local Action.—Some chemical action takes place in practically all batteries, even when the battery is not being used. This wasteful chemical action is called **local action.** It is ordinarily due to small pieces of some impurity (as carbon) present in the zinc. All over the zinc plate these small particles, together with the zinc, form tiny cells. The current from these cells does not pass through the outside conductor, but wastes itself in producing heat in the cell. The use of chemically pure zinc would prevent local action, but this is too expensive a remedy.

Local action can be largely prevented by *coating the zinc with mercury.* This is called *amalgamation.* When mercury is rubbed over a clean zinc plate, it dissolves some of the zinc, forming a *zinc amalgam,* but it has no action on the impurities. This zinc amalgam covers the impurities, and as they are no longer exposed to the action of the acid, local action stops. The zinc is dissolved from the amalgam when the battery is in use, but the mercury is not acted on and remains on the plate. This mercury dissolves more zinc, and keeps the surface of the zinc plates pure zinc amalgam, thus preventing local action.

The result of the local action is often seen in dry cells, where the outside zinc case is eaten through in spots, long before the battery should be exhausted.

What is local action? What causes it? What is the objection to it? How may local action be prevented? Why does this accomplish the desired result?

409. Polarization.—A cell is said to be **polarized** when its action is interfered with by deposits on its plates. In a voltaic cell the polarization is caused by the layer of hydrogen that forms on the copper plate. This acts in two ways to arrest the action of the cell. Hydrogen is a poor conductor and offers great resistance to the passage of the current. Moreover, the electrodes of the cell have now, in reality, become hydrogen and zinc, and a cell with such electrodes would tend to send a current in a direction opposite to the original direction, that is, a *back electromotive force* is produced. To *depolarize the cell,* we must remove this hydrogen by mechanical or chemical means.

Some cells have been devised in which the hydrogen was brushed off by mechanical means, but none of these are now in use. A more convenient and effective method is to surround the plate with some substance that will supply oxygen to combine with the hydrogen and form water. Manganese dioxide (MnO_2) is often used for this purpose. In the description of the Daniell cell you will find another method used. (§ 412.)

What is polarization in a cell? What causes it? What is the result? How may polarization be prevented? Name a common depolarizer.

410. Electromotive Series.—Many different pairs of plates can be used as electrodes in a voltaic cell. With a given electrolyte, the metals can be arranged in such an order that we can tell at a glance which plate of a pair will become the positive plate and which the negative. Such a series, for use with sulphuric acid solution as the electrolyte, is the following:

+ Carbon
Copper
Nickel
Iron
Lead
— Zinc

The strongest cells are produced with plates as far apart as possible in this series. This shows why carbon and zinc are generally used. Primary cells are of less relative importance than formerly, and we shall describe only two of the most common.

Do all metals give the same E. M. F. in a cell? Do all electrolytes give the same results? What is the electro-motive series? Where does carbon stand in the series? Copper? Zinc? Why are carbon and zinc so frequently used?

411. The Leclanché or Carbon Cell.—This cell has zinc and carbon for its electrodes, with ammonium chloride (sal ammoniac, NH_4Cl) as the electrolyte. The depolarizer is manganese dioxide (MnO_2), which yields oxygen to unite with the hydrogen and forms water. The process of depolarizing is rather slow, so that this cell cannot be used continuously for any considerable time. Hence it is called an "open circuit cell." (Fig. 378.)

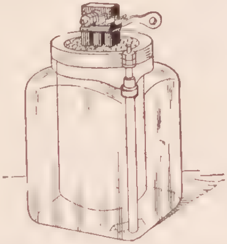


FIG. 378. A Leclanché Cell

The cell is made in many different forms. Sometimes the MnO_2 is packed in a bag around the carbon. In other forms the carbon and MnO_2 are ground together and molded into a cylinder which is then baked. One of the commonest forms is the "dry cell."

In this the zinc is the containing cup and a carbon stick the central rod. The sal ammoniac solution is mixed with some neutral absorbent, such as starch, or plaster of Paris, and forms a damp solid. When the cell becomes really dry, it ceases to act. (Fig. 379.)

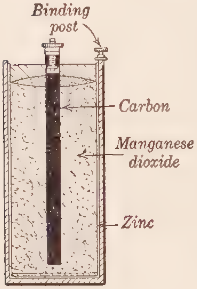


FIG. 379. Dry Cell

Carbon cells are used for operating door bells, annunciators, and isolated telephone plants. Dry cells are used for the above purposes, as "B batteries" in radio receivers, and to furnish the current for the spark ignition of gas and gasoline engines, though for these purposes they are now usually replaced by storage cells.

What electrodes are used in the Leclanché cell? What is the electrolyte? What is the depolarizer? What is a dry cell? Is it really "dry"? Why can not a dry cell be used on closed circuit? Mention several uses of the dry cell.

412. The Daniell Cell.—In this cell a different device for preventing polarization is employed. The plates are zinc and copper, as in Volta's cell, but two liquids are employed, zinc sulphate surrounding the zinc plate and copper sulphate surrounding the copper plate (Fig. 380). Zinc is dissolved from the zinc plate, and copper is deposited on the copper plate, and there is therefore no polarization. The liquids are sometimes kept apart by means of a porous jar, which contains the zinc and zinc sulphate, and stands in the copper sulphate. This keeps the liquids from mixing, but permits chemical action between the liquids, where they meet in its pores.

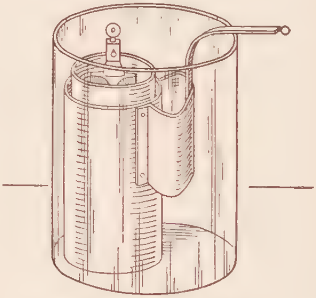


FIG. 380. Daniell Cell

In the *gravity form* of this cell (Fig. 381) the zinc is at the top of a jar and the copper at the bottom. The copper sulphate solution, being more dense than the zinc sulphate solution, is kept at the bottom of the jar by gravity (hence the name of the cell).

The chief advantage of the Daniell cell is the constancy of its e.m.f., if the liquids are kept from mixing. It requires more attention than the carbon cell, and its e.m.f. is lower.

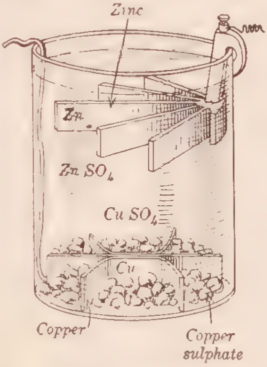


FIG. 381. Gravity Cell

What are the electrodes in the Daniell cell? The electrolyte? The depolarizer? Why does the cell not polarize? Where does the copper come from that deposits on the plate? How are the two liquids kept apart? Draw a diagram of the complete cell. What is a gravity cell? Why is it so called? What advantage has the Daniell cell over the dry cell? What disadvantage?

EXERCISES

1. What are the necessary parts of a primary electric battery?

2. What is the source of the current obtained from a primary battery?

3. Draw a diagram of a simple cell, and explain its action.

4. What do you mean by ionization? What is an ion? What function do they perform in a cell? Is ionization essential in the operation of a cell?

5. Could kerosene be used as the electrolyte in a cell? Could we substitute any other acid for sulphuric acid in a simple cell? Could acetic acid be used?

6. What does e.m.f. mean? Define potential. Try to show the similarity between an electric circuit containing a battery and a water system containing a pump.

7. Is there anything in a pumping system analogous to the e.m.f. of an electric system? Is there anything analogous to potential?

8. It is considered unwise to use an iron propeller and a bronze shaft on a vessel operating in salt water. Can you suggest a reason?

9. Would it be wise to use galvanized nails to fasten copper plates on a boat? Give reason for your answer.

10. A yacht, the plates of which were made from an alloy, was found to leak so badly after three months in salt water that the vessel was pulled to pieces and sold for scrap metal. Can you suggest a reason for the leaking?

11. What is local action, and how may it be prevented? Which of the possible ways is generally used?

12. What is polarization and how does it affect the operation of a battery? How may it be avoided?

13. Sketch, describe and explain the action of the Daniell cell. How does it differ from other cells with regard to polarization? For what type of work is it best fitted?

14. Sketch, describe and explain the Leclanché cell. How is polarization avoided? For what type of work is it best fitted? Would it be wise to use a Daniell cell for this type of work? If not, why not?

15. Of what type of cell is the dry cell a form? What are its principal characteristics? Is it really dry?

16. A two year old dry cell, that has never been used, will give no current. Can you suggest a possible cause and remedy?

17. Is the battery a satisfactory source of energy? Give reasons for and against its use.

18. What kind of battery would you use to operate a telegraph system? The door bells in an apartment house? A toy electric rail road? Electric lights for a Christmas tree? Explain in each case why the battery you name is suitable.

CHAPTER XLV

MAGNETIC EFFECTS OF CURRENTS

413. Oersted's Discovery.—Let a wire be stretched above a compass needle and parallel to the direction of the needle (Fig. 382). When a current is passed through the wire from south to north, the north pole of the needle turns toward the west. When the current is reversed, the direction of the deflection of the needle is also reversed. If the needle is placed above the wire, similar deflections are obtained, but in each case the opposite to the first direction. Hence we conclude that **the current creates a magnetic field around the wire.**

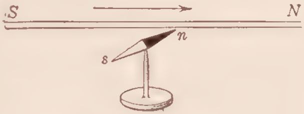


FIG. 382. Oersted's Discovery

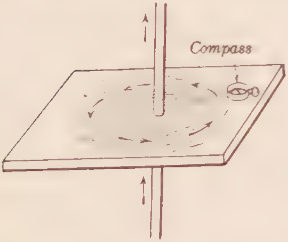


FIG. 383. Magnetic Field around Wire

The form of the lines of magnetic force of the field is shown by sending a large current through a vertical wire, which passes through a horizontal sheet of cardboard (Fig. 383). When iron filings are scattered on the cardboard, they form concentric circles around the wire, which shows that the wire is surrounded by circular lines of magnetic force. A small compass needle placed on the cardboard sets itself in the direction of the line of force. When the current is reversed the needle is reversed, showing that the positive direction along the line of force is then reversed.

The direction of the lines of force, that is, the direction in which a north pole tends to move, can be found by the following simple rule: **Imagine yourself grasping the wire in which the current flows with your right hand, as indicated in figure 384, the thumb pointing in the direction of the current. The fingers then point in the positive direction of the lines of force around the wire.**

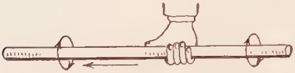


FIG. 384. Thumb Rule

A second simple rule is this: **Place the palm of the right hand on the wire with the fingers pointing in the direction of the current; the north pole of a compass needle placed on the other side of the wire will turn in the direction indicated by the thumb.** (Fig. 385.)

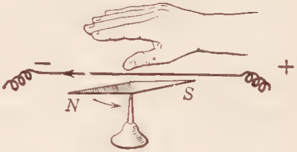


FIG. 385. Right Hand Rule

The motion imparted to the magnetic needle in these experiments and the magnetization of the iron filings show that part, at least, of the energy of the current is outside the wire that carries the current and in the field surrounding the wire. We shall see later the importance of this in Electrical Engineering.

What effect is produced when a wire carrying a current is held over a magnetic needle? If the current is reversed, what happens? What does this show? How may the lines in the field be shown? State the right hand rule. Is all the energy of a current in the wire? How do you know?

414. Circular Loop.—If a straight wire carrying a current be bent around into the form of a circular loop (Fig. 386), the shapes of the lines of force will be changed. They will still be closed curves encircling the current, but near the center of the loop they will be nearly straight and perpendicular to the plane of the loop. These would also be the shapes of the lines of force of a magnet, if it had the form of a disk bounded by the wire, the poles being on the faces of the disk. Hence the current behaves like such a disk magnet. By applying the right hand rule (§ 413), we see that the north pole of the magnet is toward the observer when the current is counter-clockwise.

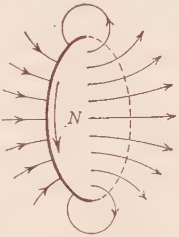


Fig. 386. A Disk Magnet

Why does a circle of wire carrying a current behave like a magnet? How can you find the polarity of the magnet thus formed?

415. Tangent Galvanometer.—A galvanometer is an instrument for detecting and measuring currents. When an electrician needs to know whether there is any current in a wire, he sometimes brings a compass needle near the wire to see whether it will be deflected. This is a simple form of galvanometer. A circular loop through which the current is led, having a compass needle at its center, is called a **tangent galvanometer** (Fig. 387). If the galvanometer is turned so that the axis of the magnet is in the plane of the loop when there is no current, on the passage of a current the north pole of the needle will be urged in the positive direction along a line of force and the south pole in the opposite direction. The deflection of the needle is shown by a long index attached to the needle. The tangent of the deflection is proportional to the current. By the tangent of an angle we mean that, if the angle is in a right-angled triangle, its tangent is the side opposite it, divided by the side adjacent to it (Fig. 388).

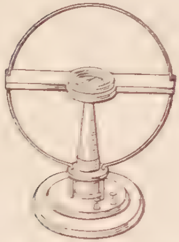


Fig. 387. Tangent Galvanometer

What is a galvanometer? Describe the simplest form. Describe a tangent galvanometer. Why is it called a "tangent" galvanometer? What causes the needle to deflect?

416. Reflecting Galvanometer.—Galvanometers for detecting *very* small currents were first devised by William Thomson (Lord Kelvin) for detecting the feeble currents sent through a transatlantic cable. In one form a coil of a great many turns of wire surrounds a magnetized needle. When a current passes in the coil, the effects of the separate turns are added and produce a magnified deflection of the needle. This is called a **moving magnet** galvanometer.

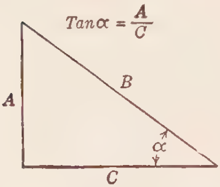


FIG. 388.

In a second form (Fig. 389) a small loop of wire, through which the current passes, is suspended between the poles of a large horseshoe magnet. When the current passes, the loop acts like a small magnet, and tends to turn its faces toward the poles of the large magnet. This instrument was devised by Thomson for use in recording cable signals, and it is still so used. The galvanometer built on this principle is usually called a **moving coil,** or **d'Arsonval,** galvanometer.

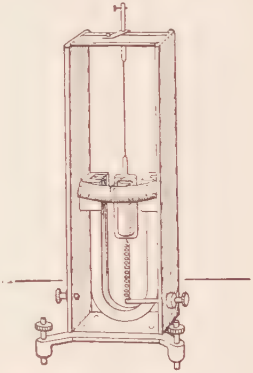


FIG. 389. D'Arsonval Galvanometer

By instruments such as these, very minute currents can be detected; and the sensitiveness is increased by an optical device. A beam of light is reflected from a small mirror attached to the moving needle or coil and falls on a distant scale. Very small currents produce quite large movements of the spot of light.

What are the two main types of galvanometers? How does each operate? What is a reflecting galvanometer? Why is it so sensitive? What is a d'Arsonval galvanometer?

417. Force on Current in Magnetic Field.—Suspend a wire *W* vertically, so that it hangs between the poles of a horseshoe magnet and its lower end dips into a mercury trough *A* (Fig. 390*a*). Pass a current through the wire in the direction shown by the arrows. The wire will move in the direction of the arrow *b*. Reverse the current and the wire will move in the opposite direction. This shows that **in a magnetic field, a wire carrying a current tends to move in a direction at right angles both to the direction of the field and to the direction of the current.**

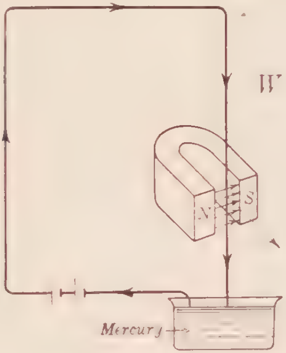
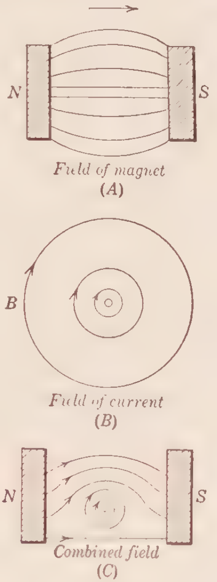


FIG. 390*a*.



Field of magnet
(*A*)

Field of current
(*B*)

Combined field
(*C*)

FIG. 390*b*.

A magnetic field exerts a force on a current

To understand the reason for this, examine figure 390*b*. *A* shows the field of the magnet, *B* the field around the wire when the current is flowing away from you, and *C* the combined field. Notice that in *C* the strength of the field above the wire is increased, because it is the sum of the field of the wire and that of the magnet, while the strength of the field below the wire is much decreased, because the two fields are opposed. Lines of force behave somewhat like stretched rubber bands, so that the wire, because of the crowded field above it, will be pushed down. Reversing the current will, of course, reverse the crowding of the lines of force, and the wire will be pushed up. A simple rule to enable you to remember which way the wire moves is: *a wire carrying a current in a magnetic field tends to move away from the side on which its lines are added to those of the field.* This is the principle made use of in the electric motor (§ 485).

Fig. 391. Lord Kelvin (William Thomson), an eminent Scotch physicist (1824-1907), inventor of many instruments, is here explaining his improved Mariner's Compass.

What happens when a wire carries a current in a magnetic field? In what direction is the wire urged? What is the probable reason for this? Show in a diagram how the crowding of the lines of force takes place.

418. Forces Between Electric Currents.—Each of two wires carrying currents has a magnetic field, as if it were a magnet. We should therefore expect such wires to attract or repel each other. That they do so can be shown by suspending two long wires close together and sending currents through them (Fig. 392).

If the current passes in the same direction through them (*a* and *b*) they will *attract each other.* The lines of force surrounding them tend to contract and pull the wires together. If the currents are opposite (*c* and *d*), the wires will *repel each other.* If the two wires are inclined at an angle, they *tend to move so as to become parallel, with the currents flowing in the same direction.* These actions are made use of in *ampere-balances* for the exact measurement of currents, invented by Lord Kelvin.

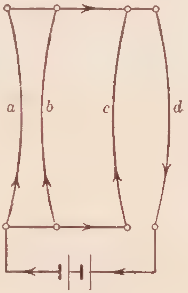


FIG. 392.

What effect does a wire carrying a current have upon a neighboring parallel wire that also carries a current? Suppose the current in one wire to be reversed. Suppose the wires are only nearly parallel.

EXERCISES

1. What influence has a current-carrying wire upon a magnetic needle, when the needle is parallel to the wire and near it? Explain the cause of this influence.

2. How could you determine whether a loose wire had a current flowing in it? If it did, how could you determine the direction of the current?

3. Name a practical application of the fact that a current-carrying wire affects a nearby magnetic needle.

4. What are the essential parts of a galvanometer? Sketch, and explain the use of a simple galvanometer.

5. What are the essential differences between the various types of galvanometers? What are the essential similarities?

6. What is the effect of two adjacent current-carrying wires on each other? How does the relative direction of the current affect the results?

CHAPTER XLVI

ELECTROMAGNETS

419. Magnetic Field of a Solenoid.—A solenoid is a wire wound in many turns on a tube of insulating material (Fig. 393). When a current flows in the wire, each turn produces a magnetic field, and inside the solenoid the fields are added together, so that the lines of force run parallel to the axis. The strength of the field is greater, the closer the turns are together and the stronger the current is. Such a solenoid, carrying a current, acts on outside magnets and on other solenoids as if it were a bar magnet. The direction of the lines of force inside the solenoid is found by the rules of § 413. The following special rule is also useful: **Grasp the solenoid with the right hand, so that the fingers curve around it in the direction in which the current flows; the extended thumb then points toward the north pole of the solenoid** (Fig. 394). Looking at the end of a solenoid, so that the current moves clockwise, the enclosed lines of force point forward as a screw in wood. (Fig. 395.)

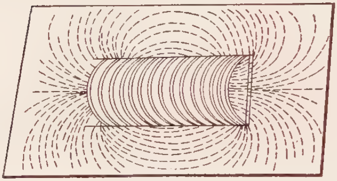


Fig. 393. Magnetic Field Surrounding a Solenoid

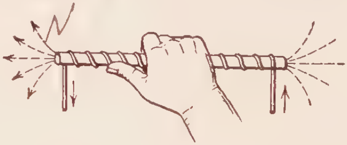


Fig. 394. Rule for Polarity of Coil

What is a solenoid? How may lines of force be made to pass through it? Upon what does the strength of the field depend? What determines the polarity of the solenoid? State the rule for polarity.

420. Electromagnet.—The magnetic field inside a solenoid that carries a current magnetizes iron placed in the solenoid. The iron core increases the number of magnetic lines passing from end to end of the solenoid, because the *permeability* of iron is greater than that of air (§ 373). Such an arrangement is an *electromagnet*.

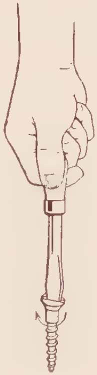


Fig. 395. Screw Rule

When the electromagnet is made in the form of a horseshoe, the magnetic lines become closed curves, passing, in the solenoid, from the south pole to the north pole and, in the air, from the north pole around to the south pole. (Fig. 396.)

If an armature or "keeper" of soft iron is placed across the poles, the air gap disappears, and the magnetic lines are wholly in an iron circuit. The force with which the armature is drawn to the electromagnet, or the *lifting power*, is very great when the windings are close together and a strong current is used. Figure 397 shows an electromagnet for lifting large masses of iron.

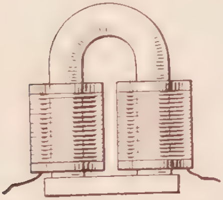


Fig. 396. Electromagnet

What happens to a piece of iron placed in the solenoid when a current flows? Define an electromagnet. What is the circuit of the lines of force in a horseshoe magnet? What is the armature? Upon what three things does the lifting power of the magnet depend?

421. Electric Bells.—The electric bell is a widely used application of the electromagnet. It consists of an electromagnet, an armature attached to a straight spring, and a gong that is struck by a hammer attached to the armature (Fig. 398). When no current passes through the electromagnet, the spring presses against a screw, and acts as a key in a circuit that contains a push-button and a battery. When the button is pushed, the circuit is closed, and a current flows. The armature is then attracted by the electromagnet, and the hammer strikes the gong.

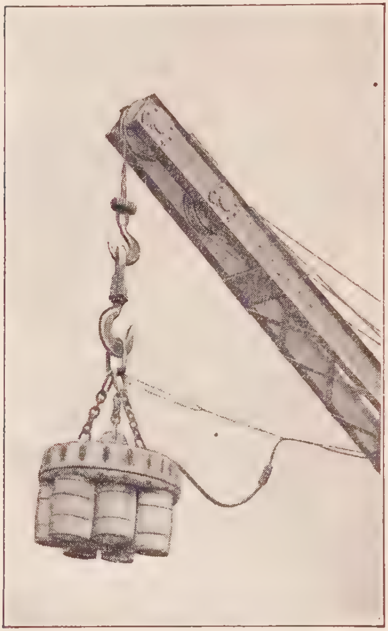


Fig. 397. Electromagnet, Lifting Kegs of Nails

The movement of the armature breaks the circuit through the spring, and the armature, being no longer attracted, flies back and again completes the circuit. The action is rapidly repeated as long as the push-button is pressed.

When the bell will not ring, the trouble is usually either an exhausted battery or a dirty contact between screw and spring.

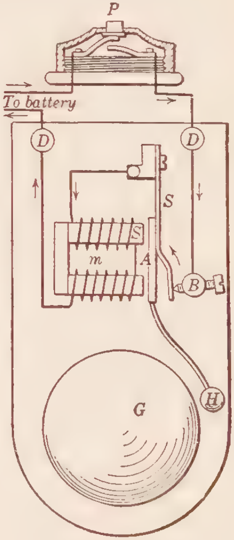


Fig. 398. Electric Bell

Describe the essential parts of the electric bell. Give the purpose of each part.

What happens when the button is pressed? Why does the bell keep ringing?

422. Telegraph Sounder.—One of the earliest applications of the electromagnet was in the construction of instruments for sending and receiving signals by means of electric currents.

Figure 399*a* represents the essential parts of the simplest telegraph for sending messages from *P* and receiving them at *Q*.

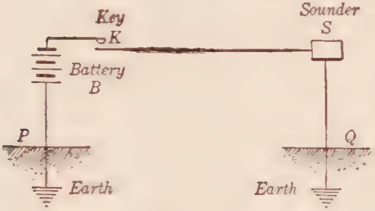


FIG. 399*a*. Telegraph Line

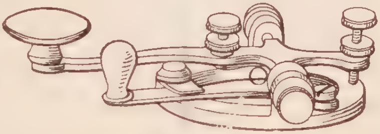


FIG. 399*b*. Telegraph Key

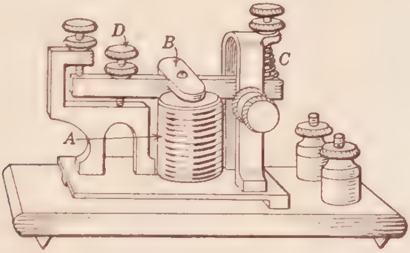


FIG. 399*c*. Telegraph Sounder

The ends of the wire from *P* to *Q* are connected to plates embedded in the earth. Thus the electric circuit consists of this wire and adjacent parts of the earth. In this circuit there is a battery, *B*, and a key, *K* (Fig. 399*b*), for opening and closing the circuit at *P*, and a sounder, *S* (Fig. 399*c*), at *Q*.

The principal part of the sounder is an electromagnet, *A*, the windings of which form part of the telegraph circuit.

Above the electromagnet is a pivoted armature, *B*, which is attracted by the electromagnet when a current flows, and is drawn away by a spring *C* when the current ceases. At each downward movement of the armature an adjustable contact point *D* attached to it strikes a stop and produces a sharp metallic click. Thus a click is heard by the observer at *Q* each time the key is pressed by the operator at *P*. A lighter click is produced by the rise of the armature when the circuit is broken. When the key at *P* is pressed for an instant only, the two clicks follow one another in quick succession, and the signal is called a *dot*. When the key is pressed for a longer interval, the interval between the clicks is longer, and the signal is called a *dash*. Different combinations of dots and dashes are used to represent letters. The Morse code, commonly used in the U. S., is given below.

TELEGRAPH CODE. MORSE.

A - —
B — - - -
C - - -
D — - -
E -
F - — -
G — — -
H - - - -
I - -
J — - — -
K — - —
L ——
M — —
N — -
O - -
P - - - - -
Q - - — -
R - - -
S - - -
T —
U - - —
V - - - —
W - — —
X - — - -
Y - - - -
Z - - - -

What are the essential parts of a simple telegraph to send messages one way? What happens in the coils of the sounder when the key is pressed? To the armature? How is a dot made? A dash? What is meant by a telegraph code?

423. Telegraph Relay.—When the distance between the stations *P* and *Q* is very great, the resistance of the long line prevents the passage of sufficient current to work the sounder. To overcome this difficulty Joseph Henry invented the relay. (Fig. 400.)

The *relay* is similar to the sounder in consisting of an electromagnet and a movable armature. The windings of the electromagnet are in series with the telegraph line, and when a current passes the armature acts as a key to close a circuit that consists of a sounder and a second battery. By winding many turns of fine wire on the magnet and using a very light armature, the relay is made much more sensitive than the sounder, and it will act with a current that would be too small to give audible clicks if applied to the sounder. The resistance in the circuit of the sounder being small, a sufficient current will be supplied by a local battery of a very few cells.

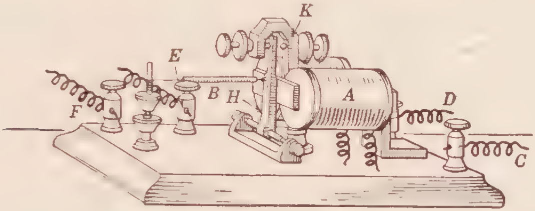


Fig. 400. Telegraph Relay

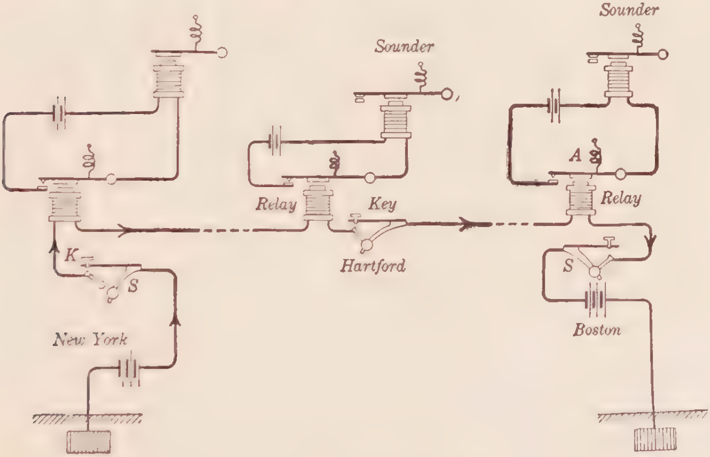


Fig. 401. Telegraph Line

The relay is therefore in effect a sensitive electrical telegraph key, which operates a local circuit, consisting of a battery and sounder.

What is a relay? Why does it operate with a very small current? What is its purpose in a telegraph system? What is the local circuit? Of what does it consist?

424. Connection of Instruments to Line.—To enable signals to be sent and received at each end of the line, there is at each station a key, a sounder, and a relay connected as indicated in figure 401. When the sending of a message by means of the key *K* has been completed, the switch *S* is closed, and the line circuit is thus completed. Signals can then be received from the other station. At any intermediate station on the line there is a similar equipment, only one wire being needed for the whole line.

What instruments are needed to send signals both ways on a line? What is the purpose of the switch beside the sending key?

EXERCISES

1. What is an electromagnet? What are its essential parts?

2. Knowing the direction of the current in an electromagnet, how can you determine the position of the north pole?

3. What is the use of the iron core of an electromagnet? Is iron or steel the better substance for the core? Why?

4. Mention some of the practical uses of an electromagnet.

5. Sketch, describe and explain the electric bell.

6. What are the essential parts of a telegraph system? What is the use of the key? Of the sounder? Wherein do conditions in a telegraph circuit and in a bell circuit differ?

7. What is the use of a relay? Why is the relay necessary? Would one be necessary on a short line?

8. Why is a sounder necessary if a relay is used? Is the sounder worked by the line current? Why not wind many turns of wire on the sounder and dispense with the relay?

9. What are the conditions in a telegraph circuit when no message is being sent?

CHAPTER XLVII

LAWS OF ELECTRIC CURRENTS

425. Unit Current.—To enable us to plan for the use of electric currents in lighting buildings and streets, in running street cars, and for other purposes, we need some simple rule for calculating currents. The chief aid in doing this is a law discovered by G. S. Ohm in 1826. Before stating it we must explain the terms used in it.

A current of electricity is invisible, and we cannot measure it as we measure a flow of water. We must measure it by some one of its effects. The effect chosen for defining the legal unit of current is the separation of an element from a compound in an electrolyte by the passage of a current.

If one platinum wire is joined to the zinc plate of a cell and another to the copper plate, and the free ends of the wires are held in a solution of silver nitrate, silver will be deposited on the wire connected to the zinc plate. If the strength of the solution and the strength of the current be kept constant, the deposit will increase at a constant rate.

The ampere is defined legally as the strength of a current which would deposit silver at the rate of .001118 gram per second under certain specified conditions.

Why are electric units necessary? What effect of the current is selected in defining the unit of current? What is the name of the unit? Define the unit. How is the apparatus arranged to determine it?

426. Resistance.—To cause a flow of water, oil, or any fluid in a pipe by means of a pump, a difference of *pressure* must be produced at the ends of the pipe by means of the pump, in order to overcome the resistance of the pipe to the flow. To produce an electric current in a wire by means of a voltaic cell, a difference of *potential* must be applied to the ends of the wire by means of the cell. The wire evidently has a property corresponding to the resistance of the pipe to the flow of water. This we call the *electrical resistance* of the wire.

An incandescent lamp is essentially a wire heated by a current of electricity. Connected to a suitable battery (or generator), it glows brightly. Two lamps connected in series, that is, so that the whole current passes through each of them, glow feebly; three, still more feebly; and so on. By joining lamps in series we add their resistances and cut down the current.

What is electrical resistance? Why does it exist? If lamps are joined in series, what effect is produced? Why?

427. Effect of Dimensions of Wire.—To study the resistances of wires, let a circuit (Fig. 402) be formed by connecting in series a constant voltaic cell, a galvanometer, and a german silver wire, the contacts with the wire being adjustable, so that different lengths of it can be used. It will be found that the longer the part of the wire in the circuit the smaller the current is. **The resistance of a wire is proportional to its length.** A wire 6 ft. long has twice as great a resistance as a wire 3 ft. long.

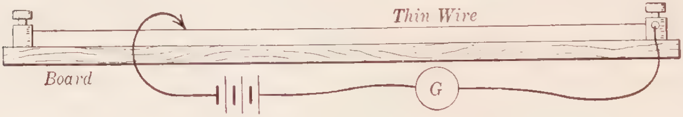


FIG. 402. Resistance of Wires

Next let two german silver wires, one of which is twice as long and of twice as great a cross section as the other, be tried in the circuit in succession. The currents will be equal. Hence the resistances of the wires are equal. The increase of resistance due to the double length is compensated by the decrease due to the double cross section. Hence **the resistance of a wire is inversely proportional to its cross-sectional area.** No. 30 copper wire is half as thick as No. 24 and thus has one-fourth the cross-sectional area. Hence for equal lengths the resistance of the former is 4 times that of the latter.

How is the resistance of a wire affected by increasing its length? By increasing its cross-sectional area? If the diameter is made twice as great, how will its resistance be changed?

428. Effect of Material.—Using the same arrangement as in the preceding we can compare the resistances of wires of different materials. For example, a platinum wire 1 ft. long and a copper wire 7 ft. long, of the same cross section, when placed in succession in the circuit, allow equal currents to pass. Hence the platinum has 7 times as great resistance per foot as the copper, or the *specific resistance* of platinum is 7 times that of copper. **The resistance of a wire depends on the material of which it is made.**

Resistance also depends on *molecular condition.* The resistance of hard drawn copper is greater than that of soft copper. Heating a wire changes its molecular condition. A rise of temperature increases the resistance of a metallic conductor, but decreases that of carbon and of electrolytes. The resistance of a glowing carbon filament in the older type of incandescent lamp is about half its resistance when cold. The tungsten filament has a much higher resistance when hot than when cold.

Do all materials have the same resistance? Does the same material have the same resistance under all conditions? Is the resistance of a hot metallic wire more or less than that of a cold one? Is this also true of carbon?

429. Unit of Resistance.—The simplest unit of resistance would be that of a standard length of wire. But it is difficult to obtain wires of pure metals. Mercury has therefore been selected as the standard, because it can be obtained pure.

The **legal unit of resistance,** called the **ohm,** is defined as **the resistance of a uniform column of mercury at 0° C., the mass of the mercury being 14.4521 grams and the length of the column 106.3 cm.** This column is of 1 sq. mm. cross section. (The mass was so chosen.) The resistance of 39 ft. of No. 24 soft copper wire is 1 ohm. The same length of No. 30 copper wire has a resistance of 4 ohms.

What is the legal unit of resistance? How is it defined? After whom is it named?

430. Conductance.—For some purposes it is more convenient to consider the **conductance,** C, of a conductor than its resistance, R. Conductance is the reciprocal of resistance. $C = 1/R$. It may be thought of as the capacity of a body for conducting a current.

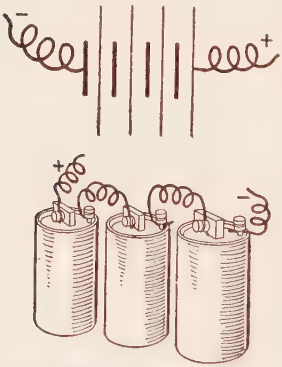


Fig. 403. Three Cells in Series

Define conductance. If you double the resistance of a circuit, what happens to its conductance?

431. Electromotive Force.—The electromotive force in a circuit in which there is a single cell has already been defined as the e.m.f. of the cell. We can obtain different e.m.f.'s in a circuit by joining a number of cells *in series*, that is, so that the copper of each is joined to the zinc of the next (Fig. 403). Since the copper of the first is joined to the zinc of the second, they are necessarily at the same potential, just as the top of the first step in a stair is at the same level as the bottom of the second step. Thus the difference of potential between the zinc of the first cell and the copper of the second is twice as great as the difference of potential of the two plates of a single cell. By joining a number of similar cells in series, we obtain a difference of potential between the zinc of the first and the copper of the last that is *proportional to the number of cells*, just as the height of a stair is proportional to the number of steps.

The e.m.f. of a battery of similar cells in series is the e.m.f. of a single cell multiplied by the number of cells. This is also the e.m.f. of a circuit formed by joining conductors in series with the battery. The unit of e.m.f. will be defined in the next paragraph.

How are cells joined in series? What is the object of so doing? How would you find the e.m.f. of a number of similar cells?

432. Ohm's Law.—The current, I, in a circuit is directly proportional to the e.m.f., E, of the circuit and inversely proportional to the total resistance, R, of the circuit.

This law can also be writen as an equation

$$I = \frac{E}{R}$$

if we choose a suitable unit of e.m.f. From the equation we see that E must be unity if I and R are each unity. The **unit of e.m.f.** is therefore **the e.m.f. that will produce unit current (one ampere) in a circuit of unit resistance (one ohm).** The unit of e.m.f. is called the **volt.** The e.m.f. of a simple voltaic cell is about 1 volt, that of a dry cell about 1.5 volts. The voltage of the currents used for house lighting is usually 110 volts, that is, there is a difference of potential of 110 volts between the ends of the wires connected to a lamp when the lamp is not lighted.

State Ohm's law. Express the law in a formula. What is the unit of e.m.f. called? How large is it?

433. Flow in a Simple Circuit.—By a simple circuit we mean one that has nowhere any side branches, like roads diverging from the highway or tributaries flowing into a river. In a simple circuit *as much electricity must flow past one point of the circuit as past any other point.* In this respect electricity acts like a stream of water.

What is a simple circuit? How does the current in one part of the circuit compare with that in another part?

434. The Coulomb.—The quantity of electricity that passes in one second through the cross section of a conductor in which a current of 1 ampere is flowing is called a **coulomb.** This is the unit of electrical charge used in practical calculations. For example, if the current in an incandescent lamp is $\frac{1}{2}$ ampere, the quantity of electricity that flows through it in a minute is $60 \times \frac{1}{2} = 30$ coulombs.

From the definition of the coulomb it is evident that **an ampere is equal to a flow of a coulomb per second.**

Define the coulomb. What is the relation between the coulomb and the ampere?

435. Ohm's Law for Part of a Circuit.—Ohm's law, in the form in which it has been stated, refers to a complete circuit. But with a slight change it also applies to any part of a circuit.

Consider a wire that forms part of a circuit in which a current is flowing. A fraction of the e.m.f. of the circuit may be considered as acting on the wire, the rest being considered as acting on the rest of the circuit. The part acting on the wire is the difference of potential at the ends of the wire, just as the part of the whole fall of level in a river, which determines the flow in a certain length of the river, is the difference of level at the ends of that length.

If the difference of potential at the ends of the wire is

$V_1 - V_2$, and the resistance of the wire is r, then the current I in the wire is given by

$$I = \frac{V_1 - V_2}{r}$$

Is Ohm's law applicable to parts of a circuit as well as to the whole? Distinguish between difference of potential and e.m.f. Give the formula in terms of difference of potential.

436. Fall of Potential in a Circuit.—From this last relation we see that

$$V_1 - V_2 = Ir$$

The fall of potential in a conductor is equal to the product of the current and the resistance of the conductor.

When a number of conductors are in series, the current is the same through all. Hence **the falls of potential are proportional to the resistances.** In figure 404*a* the current from the generator G passes through the three conductors, C, D, E, the resistances of which are 10, 20, and 30 ohms respectively. If a voltmeter shows a drop of potential from A to M of 2 volts, it will show 4 volts from M to N, 6 volts from N to B, and 12 volts from A to B.

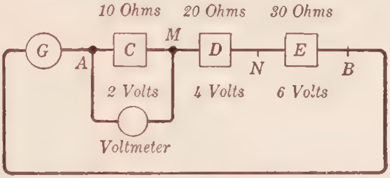


FIG. 404*a*. Fall of Potential in a Circuit

What is meant by the fall of potential in a conductor? What two factors determine it? In a series circuit, what relation exists between the resistances in part of the circuit and the falls of potential in them? If the fall in one part of the circuit is twice that in another part, how do their resistances compare?

EXERCISES

1. What is the unit of current strength? How is it determined?
2. What is electrical resistance? What is the unit? How is it determined?

3. What effect have the dimensions of a wire upon its resistance?

4. Can you give an instance in which an increase of resistance in a circuit is desirable?

5. Design, sketch, describe and explain an apparatus for changing the resistance in a circuit.

6. Is it possible for two pieces of copper wire, of exactly the same dimensions, to have different resistances?

7. Define conductance. If wire A has twice the resistance of wire B, how will the conductance of A compare with that of B?

8. Define electromotive force. Name and define its unit.

9. What is meant by joining cells in series? What effect has this upon the e.m.f. of the circuit? Why is this effect produced?

10. State Ohm's law.

11. Define coulomb. Explain the difference between one coulomb and one ampere.

12. How is the fall in potential in a circuit related to the resistance of the different parts of the circuit?

PROBLEMS

1. A current deposited 3 g. of silver in 20 minutes. How many amperes were flowing?

2. A large metal dish is to have 80 g. of silver plated on it, using a current of 2 amperes. How long must the dish be kept in the plating bath?

3. How will the resistance of a wire be changed by doubling both its length and diameter?

4. The length of a wire was halved, and its diameter doubled. How did this change the resistance?

5. The resistance of 39 ft. of No. 24 copper wire is 1 ohm. What is the resistance of 1 mile of this wire? Of 1 ft.?

6. The resistance of 80 ft. of copper wire is 4 ohms. I require a resistance of 76 ohms. How many ft. must I use?

7. The resistance of an alloy is 7 times as great as that of copper. A 1000 ft. length of copper wire has a resistance of 40 ohms. How long must a wire of the alloy, having the same diameter as the copper wire, be to have the same resistance? To make a 1000 ft.

wire of the alloy have a resistance of 40 ohms, its diameter must be what compared to that of the copper wire?

8. Find the missing quantity in each of the following cases.

	I	E	R		I	E	R		I	E	R
(a)	3	110	x	(d)	x	110	55	(g)	4	x	3
(b)	5	220	x	(e)	x	4	3	(h)	3	x	115
(c)	7	6	x	(f)	x	6	1	(i)	17	220	x

9. How many coulombs will a current of 2 amperes, flowing for 3 minutes, deliver?

10. A current of ½ ampere flows through a lamp of 50 ohms resistance, and delivers 12,500,000 coulombs. How long was the lamp used?

11. The resistance of *AB* is 10 ohms (Fig. 404*b*), *BC* 20 ohms, and *CD* 15 ohms. The current flowing is 4 amperes. What is the drop in potential in *AB*, *BC*, and *CD*?

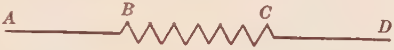


FIG. 404*b*.

12. In the figure above, if a current of 3 amperes flows from *A* to *D*, and the drop of potential from *A* to *B* is 3 volts, from *B* to *C* 21 volts, and from *C* to *D* 15 volts, find the resistance of each wire, and the total resistance.

13. A lamp of 55 ohms resistance, a wire of 5 ohms resistance, and a rheostat of 20 ohms resistance are connected in series. What e.m.f. will force a current of 2 amperes through the circuit? What will be the fall of potential in each part of the circuit?

14. Ten incandescent lamps, each having a resistance of 440 ohms, are connected in parallel across a 110 volt circuit. (a) What is the total resistance of the circuit, (b) what is the total current, (c) is the current through each lamp?

15. A galvanometer having a resistance of 500 ohms is protected by joining its two terminals by a copper wire of 2.5 ohms resistance. (a) What is the joint resistance of the circuit? If the total current in the circuit is 1 ampere, how much will flow through the galvanometer?

16. Three wires of respectively 2, 4, and 6 ohms resistance are joined in parallel. What voltage is required to drive 10 amperes through this circuit, and what current will flow in each wire?

CHAPTER XLVIII

ELECTRICAL MEASUREMENT

437. Method of Measuring Resistances.—The measurement of resistances is of great practical importance. It is performed by comparing the unknown resistance with a known resistance, somewhat as two weights are compared by a balance. The arrangement used is called a **Wheatstone's bridge** (Fig. 405).

The conductor of unknown resistance, R_1, and another conductor of known resistance, R_2, form two sides of a triangle ABC. The base AC is a uniform wire, usually a meter long. One plate of a cell, for example the copper or carbon plate, is connected to A, and the other to C. Thus A is at a higher potential than C, and the potential decreases from A along ABC to C, and also from A along ADC to C. Hence there must be some point D on the wire at the same potential as B. If B and D be joined by a galvanometer, no current will flow through the galvanometer. To find the point D that is at the same potential as B, all that we need to do is to slide one terminal of the galvanometer along AC, until there is no current in the galvanometer.

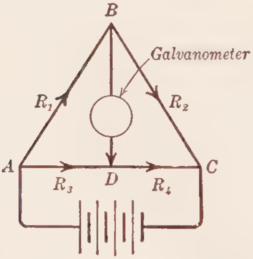


FIG. 405. Wheatstone's Bridge

When this is the case, the current along AB is equal to that along BC. Let it be denoted by I. Also the current along AD is the same as that along DC. Let it be denoted by I'.

Since the potential at B is equal to that at D, the fall of potential from A to B is equal to the fall from A to D. Hence, by the principle stated in § 436

$$IR_1 = I'R_3$$

and
$$IR_2 = I'R_4$$

Dividing the respective sides of these equations, we get:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

Now R_3 and R_4 are the resistances of two parts of the same uniform wire AC, and they are therefore in the ratio of the length of these parts. These lengths are read off on a scale placed beneath AC, and their ratio gives us the ratio of R_3 to R_4, which equals the ratio of R_1 to R_2. Hence if R_2 is known, R_1 is readily calculated.

What instrument is used to measure resistance? Describe it. Why is it sometimes called a slide wire bridge? What is the object of moving the contact along the wire? When the correct position has been found, what does it show? Why must the wire be of uniform cross section? State the proportion which holds when the adjustment is completed. Draw a diagram of the bridge and letter it.

438. Resistance Boxes.—For use with a Wheatstone bridge and for other purposes, it is convenient to have a series of resistances arranged so that any one, or any combination of them, can be used when needed. For this purpose, wires of suitable sizes are connected in series and placed in a box (Fig. 406), and the various junctions are connected to heavy brass blocks on the cover of the box. Between each two adjacent blocks a

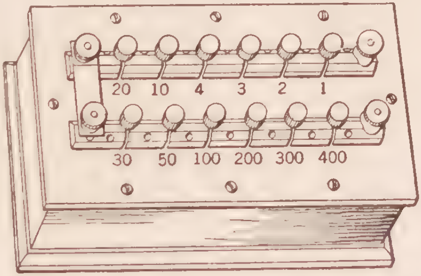


FIG. 406. Resistance Box

brass plug can be inserted. The free ends of the first and the last wires in the series are connected to binding posts on the cover.

When a cell is connected to the two binding posts and the plugs are all out, the current flows through all the wires, and the total box-resistance is the sum of the separate resistances of the wires. When a plug is inserted between two blocks, the current flows through the plug, and the corresponding resistance is "cut out," that is, the resistance of the circuit is decreased by that amount, since the resistance of the thick plug is negligible.

How is a resistance box constructed? Are the resistances joined in series or in parallel? How are the resistances added to the circuit?

439. The Circular Mil.—In measuring wire for electrical use it is customary to give the diameter in mils, the cross-sectional area in circular mils, and the length in feet.

A **mil** is one-thousandth of an inch. No. 24 wire has a diameter of 0.0201 inch or 20.1 mils. A **mil-foot** of wire is one mil in diameter and a foot in length.

A wire having a diameter of one mil has a cross-sectional area of one **circular mil.** Since the areas of circles are as the squares of their diameters, we have only to express the diameter of a wire in mils and square it, when we have the area in circular mils. The cross-sectional area of No. 24 copper wire is therefore $20.1^2 = 404.01$ circular mils.

Define a mil. A circular mil. A mil-foot. What is the cross-sectional area of a wire whose diameter is 2 mils?

440. Computing the Resistance of a Wire.—If we denote the resistance in ohms by R, the length in feet by l, the cross-section in circular mills by d^2, and the resistance of one mil-foot of the wire by K, the formula for calculating resistance is:

$$R = \frac{Kl}{d^2}$$

The resistance K of one mil-foot of copper wire is 10.4 ohms. The values of K for a number of other metals are as follows:

Iron	61.5	German Silver	181.3
Platinum	70.5	Mercury	574

What must be known in order to compute the resistance of a wire? Give the formula for the computation. What is the meaning of K in the formula? What is its value for copper? Is it greater or less for iron? For German silver?

441. Resistance of Conductors in Series.—When any number of conductors are arranged in series, that is, end to end (Fig. 407), so that the same current has to pass through all, **their combined resistance equals the sum of their separate resistances.** If the separate resistances are R_1, R_2, and R_3, and the total resistance is R,

$$R = R_1 + R_2 + R_3$$

What effect is produced by connecting resistances in series? Give the formula for total resistance.

442. Resistance of Conductors in Multiple or Parallel.—When two conductors are connected side by side (Fig. 408), they are said to be in multiple or in parallel. When the joined ends are connected to a battery, part of the current from the battery passes through one conductor and part through the other. Since the current has two paths open to it, the resistance of the part AB is less than it would be if either conductor were absent. The conductance of AB is the sum of the separate conductances. Since conductance is the reciprocal of resistance, if R_1 and R_2 are the separate resistances and R their joint resistance,

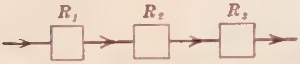


FIG. 407. Resistances in Series

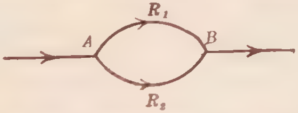


FIG. 408. Resistances in Parallel

$$\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}$$

The reciprocal of the total resistance equals the sum of the reciprocals of the separate resistances.

What is meant by connecting resistances in parallel? In multiple? How does the resistance of two circuits in parallel compare with either one alone? How does the conductance compare? State the formula for computing the joint resistance.

443. Cells in Series.—When n similar cells, each of e.m.f. E, are connected *in series* (Fig. 403), the e.m.f. of the whole battery is nE. If the resistance of each cell is r the resistance of the battery is nr. If this battery is in series with a conductor of resistance R, the total resistance is $R + nr$. Since the e.m.f. of the circuit is known, and also the resistance, we can find the current by applying Ohm's law.

What is the effect on the e.m.f. of connecting cells in series? On the resistance? What is the e.m.f. of 5 cells in series each having an e.m.f. of 1 volt? What is the resistance if each has a resistance of .2 ohm?

444. Cells in Parallel.—When n similar cells, each of e.m.f. E and resistance r, are joined in parallel (Fig. 409), the e.m.f. of the battery is the same as that of a single cell or E. But the resistance of the battery is only $1/n$ of that of a single cell or r/n. If the external resistance in the circuit is R, the total resistance is $R + r/n$. By applying Ohm's law the current I can be found.

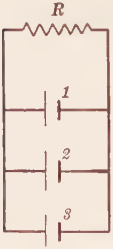


Fig. 409. Cells in Parallel

What is the e.m.f. of cells if connected in parallel? What is the combined resistance when in parallel?

445. Ammeters.—The ordinary ammeter is a d'Arsonval galvanometer, in which the coil is mounted between pivots, very accurately fitted. The position of the coil is controlled by two oppositely acting spiral springs, one of which also leads the current into the coil while the other leads the current away from it. Only a fraction of the current passes through the coil. The larger part of it flows through a *shunt*, that is, a wire in parallel with the coil. (Fig. 410.)

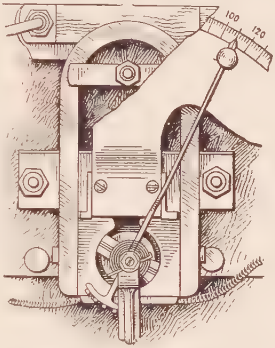


FIG. 410. Ammeter

The coil is mounted between the poles of a permanent magnet, and is connected in series with the current to be measured. The passage of the current tends to turn the coil. The rotation is controlled by the springs, so that it is directly proportional to the current passing through the ammeter. A long pointer, attached to the moving coil, swings over a scale on which amperes are marked. Such an ammeter must be connected so that the current to be measured enters at the positive binding post, as otherwise the deflection of the needle would be in the wrong direction.

Describe an ammeter. What is it used for? How is the position of the pointer controlled? Does all the current to be measured flow through the coil? Where does it flow? What is a shunt? Why does the instrument indicate the current? What care must be taken as to the direction of the current?

446. Voltmeters.—Instruments intended to measure the difference of potential between two points in a circuit are known as *voltmeters*. One common commercial form is a modified d'Arsonval galvanometer (Fig. 411*a*). It consists of a galvanometer which has a high resistance coil in series. Only a small current passes through the instrument, but all of this current goes through the galvanometer coil. As this current is directly proportional to the voltage, the scale can be marked directly in volts. Voltmeters are always connected across the line the voltage of which we wish to measure, and never in series. (Fig. 411*b*.)

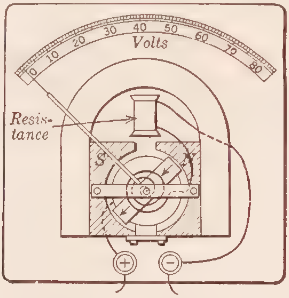


FIG. 411*a*. Voltmeter

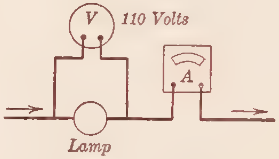


FIG. 411*b*. Ammeters Are Connected in the Line; Voltmeters Across the Line

What is a voltmeter? How does it differ from an ammeter? Why is a high resistance connected in series with the coil? How are voltmeters connected in the circuit? Diagram a circuit containing an ammeter and a voltmeter.

EXERCISES

1. Sketch, describe and explain the principle of the Wheatstone Bridge. For what is it principally used?

2. Draw a diagram of the connections of a resistance box.

3. Wherein does a voltmeter differ from a galvanometer? Wherein are they alike?

4. Wherein does an ammeter differ from a galvanometer? Wherein are they alike?

5. Why should a voltmeter have a high resistance and ammeter a low resistance?

6. Define mil, mil-foot, circular mil. What effect has doubling the diameter of a wire on the circular mils?

7. What is meant by connecting cells in series? What is the effect on the internal resistance and e.m.f.?

8. What is meant by connecting cells in parallel (multiple)? What is the effect upon the internal resistance and e.m.f.?

9. Devise an experiment to prove that the e.m.f. of a cell does not depend on the size of the plates, or their closeness together.

10. Devise an experiment to prove that the internal resistance of a cell is decreased by bringing the plates nearer together.

11. Draw a diagram of the connections of a resistance box.

PROBLEMS

1. The resistance of a wire, x, is to be found, using a Wheatstone bridge (Fig. 405). When the ratio coil R_3 has a resistance of 10 ohms, R_4 1 ohm, and the resistance box a resistance of 24.7 ohms, no current passes through the galvanometer. What is the resistance of x?

2. If R_3 is 100 ohms, R_4 1 ohm, and R_2 42.7 ohms (see figure above), the bridge balances. Find x.

3. The diameter of a wire is 0.04 in. What is (a) its diameter in mils? (b) its cross sectional area in circular mils?

4. A wire has a cross section of 140,000 circular mils. What is its diameter in mils? In inches?

5. A copper wire 0.02 in. in diameter, and 200 ft. long, will have what resistance?

6. What is the resistance of 400 ft. of German silver wire, having a diameter of 0.025 in.?

7. An iron wire 500 ft. long has a resistance of 250 ohms. What is its diameter?

8. How many ft. of platinum wire of 49 circular mils, will have a resistance of 14,000 ohms?

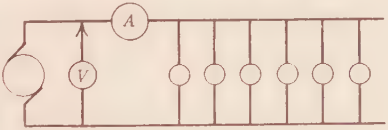


FIG. 411c.

9. Two 50 ft. lengths of No. 34 copper wire are joined in parallel. What is the resistance?

10. We wish to replace 100 ft. of No. 14 copper wire with two No. 14 copper wires joined in multiple, without changing the resistance. How long must each wire be?

11. Six lamps, each having a resistance of 72 ohms, are connected

in parallel (Fig. 411*c*). The current in the main line as shown by the ammeter *A* is 10 amperes. What is the joint resistance of the lamps? What current flows in each lamp?

12. Twelve lamps, each of 110 ohms resistance, are connected in parallel (see figure above). Each lamp requires a current of ½ ampere. What current will the ammeter *A* show? What is the joint resistance of the lamps?

13. Three wires of equal resistance are joined in parallel. Their joint resistance is 6 ohms. What is the resistance of each wire?

14. The terminal voltage in a trolley car is 550 volts. The car is to be lighted with lamps, each requiring a voltage of 110 volts, and will require from 20 to 25 lamps. How many would you use and how would you connect them?

15. A telegraph line requires a current of 0.25 ampere, and has an external resistance of 450 ohms. How many gravity cells, each with an e.m.f. of 1.06 volts, and an internal resistance of 2.2 ohms, must be used?

16. Six cells, each with an e.m.f. of 1.4 volts, and an internal resistance of 0.05 ohm are connected in parallel. If the external resistance is 12 ohms, what current will they give?

17. Six cells, each with an e.m.f. of 1.5 volts and an internal resistance of 0.1 ohm, are connected to an outside resistance of 10 ohms. Should they be connected in series or parallel to give the maximum current?

18. An automobile storage battery has 3 cells; each has an e.m.f. of 2.1 volts and an internal resistance of 0.01. The battery is used to light two headlight lamps connected in series, each having a resistance of 1 ohm. What current will flow through each lamp? If the lamps were connected in parallel, what current would flow through each lamp?

CHAPTER XLIX

CHEMICAL EFFECTS OF CURRENTS

447. Decomposition of water.—Many important industries, such as the production of aluminum from bauxite for kitchen utensils and of copper from ores of copper, have grown out of the discovery that compounds can be separated into elements by an electric current.

The first such decomposition was that of water. Pure water is practically a non-conductor, but a small trace of mineral acids, bases, or salts makes it a conductor. For example, in the arrangement shown in figure 412 an incandescent lamp on a lighting circuit is in series with plates of clean zinc in a beaker of pure water. No current passes until a small amount of sulphuric acid or common salt is dropped into the water; this makes the liquid a conductor and the lamp glows. But acetic acid or sugar will not produce the same result, though they look much like sulphuric acid and salt respectively. The reason is that acetic acid and sugar do not dissociate (§ 404).

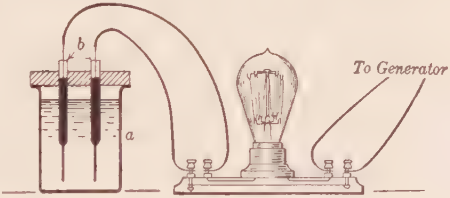


FIG. 412. Chemical Effect of Current

A convenient apparatus for decomposing water consists of a U-shaped tube *AB*, the branches having stop-cocks at the upper ends. At the bottoms are small platinum plates *P*, *P'*, connected to platinum wires p, p', which pass through the glass. A tube T, with a bulb R, is connected to the U-tube at the bottom, and is open at the top. The tubes are first filled with a weak solution of sulphuric acid. When a battery of several cells in series is connected to the wires p, p', gases are formed at the plates P, P' and rise in the branches of the tube AB. If p is connected to the copper (or corresponding) plate of the battery, gas allowed to escape at B will burn with a pale flame. This is *hydrogen.* Gas escaping from A will not burn, but it will ignite a glowing match. This is *oxygen.* The volume of the hydrogen increases twice as fast as that of the oxygen, which is in accord with the chemical formula (H_2O) of water. The oxygen is liberated at the plate, P, where the current enters the liquid, and the hydrogen at the other plate (Fig. 413).

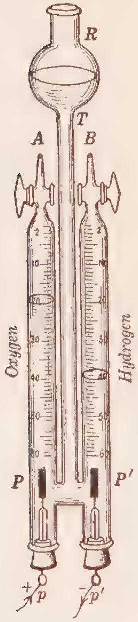


FIG. 413. Decomposition of Water

The decomposition of a compound by an electric current is called **electrolysis** and the substance decomposed is called an **electrolyte.** The plates by which the current enters and leaves the liquid are called **electrodes,** the former being the **anode** and the latter the **cathode.** A vessel containing an electrolyte and electrodes is called an **electrolytic cell.** The term **ion** has already been defined (§ 404). An electrolytic cell suitable for measuring the amounts of the substances separated is called a **voltameter.**

Does pure water conduct an electric current? Does salt added to the water cause it to conduct the current? Does sugar produce the same effect? What happens to the water when the current flows?

What two gases are liberated? Where do they appear? How may they be collected? At which terminal is the hydrogen seen? What is the process called? Define: electrolyte, electrode, anode, cathode, ion, voltameter.

448. Electrolysis of Copper Sulphate.—In a tumbler containing a solution of copper sulphate place two carbon rods to serve as electrodes, and pass a weak current of electricity through the solution. After a few seconds remove the carbon electrodes and examine them. The anode will have suffered no change, but the cathode will be coated with copper. This copper must have come from the copper sulphate, and some sulphuric acid must have been formed in the solution.

Replace the electrodes in the solution and reverse the current, so that the copper-plated carbon is the anode. After a short time the copper coating will have disappeared from the anode, and the cathode will be coated. Continue the current for a considerable time. The solution will gradually lose its color, the copper being extracted from it and deposited on the cathode.

Now substitute a thin strip of copper for the carbon anode and pass the current for a long time. The solution will maintain its color, and the copper deposit on the cathode will steadily increase. This increase is at the expense of the copper anode, which gradually becomes thinner.

If a solution of copper sulphate conducts a current what is liberated? At which electrode does it appear? Where did it come from? What is made in the cell at the same time? How could the copper be removed from the electrode? If the anode is a strip of copper, what happens?

449. Purification of Copper.—Copper bars, or ingots, as they come from a copper furnace, contain impurities, especially arsenic, which diminish the conducting power of the copper. These must be removed, and electrolysis provides a means. Great vats of copper sulphate are used, in which strips of purified copper serve as cathodes, while the ingots act as anodes. As the current passes, the copper disappears from the anodes and is deposited as pure copper on the cathodes, while the impurities drop to the bottom of the vat.

How is copper purified by electrolysis? What becomes of the impurities?

450. Electroplating.—By electrolysis it is possible to cover brass, bronze, or iron with the more expensive gold or silver, and so to add to the strength of the former the brightness, polish, and resistance to corrosion of the latter.

Figure 414 shows the arrangement for plating spoons with silver. A wooden tank is filled with a solution of silver cyanide. The spoons are the cathode of the electrolytic cell and are connected to the negative (zinc) pole of a battery or generator. The anode, a bar of pure silver, is connected to the positive pole. As the current flows, the silver of the anode passes through the solution to the spoons. In plating with gold, a solution of cyanide of gold is used, and the anode is of gold. The bodies to be plated must first be cleansed with great care, and the strength of the current must not be too great in proportion to the area of the surface to be plated or the deposit will be loose and granular.

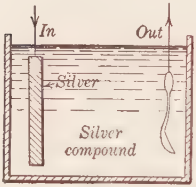


FIG. 414. Silver Plating

How is brass covered with a copper plate? To which electrode must the object to be plated be attached? What liquid is used when silver is to be deposited? Gold? How is the strength of the solution maintained? Why does the current strength have to be kept small?

451. Electrotyping.—When a great many copies of a book are to be printed, the type for a page is first set by hand or by machine, and an impression of it is then made in soft wax. This wax mold is covered with powdered graphite to make it a conductor of electricity, and it is then made the cathode in a copper plating bath. When a thin sheet of copper has been deposited on the wax, the sheet is removed, given a heavy backing of typemetal to make it rigid, and mounted on a block. It is then ready for the printing press. The copper is much harder than the original type and will stand the printing of many more copies of the book. Moreover, the plates can be preserved for use in later editions.

Describe the process of electrotyping. What is the object of the process? Why is the wax mold coated with graphite?

452. Laws of Electrolysis.—Faraday arranged a circuit so that the current passed through one voltameter and then divided into two branches, in which there were two other voltameters similar to the first. On carefully weighing the three cathodes, he found that the amount of deposit on the cathode in the first voltameter was equal to the sum of the deposits on the other two cathodes. The undivided current was, of course, equal to the sum of the currents in the two branches. From this experiment he concluded that **the mass of any substance set free in electrolysis is proportional to the current flowing and the time during which it flows.**

Let us suppose that three voltameters are arranged in series, so that the same current passes through all. If they contain different electrolytes, is there any fixed proportion in which the substances in the different cells are separated? It has been found by chemists that a definite number, called its *chemical equivalent*, can be assigned to each elementary substance, and that these numbers are proportional to the masses of the substances that combine to form compounds. Trial shows that, **when the same quantity of electricity is passed through various electrolytes, the masses of the different substances set free at the electrodes are proportional to their chemical equivalents.**

How did Faraday arrange to study the laws of electrolysis? What did he learn about the mass of a substance liberated? What two factors determine the mass liberated? Will a given quantity of electricity liberate the same mass of different substances from solutions? State the relation of the mass liberated to the chemical equivalent.

453. Electrochemical Equivalents.—The mass of a substance in grams, set free from its compounds by a current of one ampere in one second (one coulomb), is called the **electrochemical equivalent** of the substance.

ELECTROCHEMICAL EQUIVALENTS

(grams per coulomb)

Cuprous Copper	.000659	Hydrogen	.0000104
Cupric Copper	.000329	Oxygen	.0000829
Ferrous Iron	.000289	Nickel	.000304
Ferric Iron	.000193	Zinc	.000388
		Silver	.001118

The chemical equivalent of silver is equal to its atomic weight, 107.88. To deposit this weight of silver in grams, we must use

$$\frac{107.88}{.001118} = 96{,}500 \textit{ coulombs.}$$

Define electrochemical equivalent.

454. The Lead Storage Cell.—For large currents, lasting a long time, **secondary** or **storage** cells are very superior to primary cells. The lead storage cell has a negative plate of porous or spongy lead, and a positive plate of lead covered with peroxide of lead (PbO_2). The electrolyte is dilute sulphuric acid. When the plates are connected externally by a conductor, a current passes through the cell from the spongy lead to the peroxide, and through the conductor from the peroxide to the lead. The chemical actions, which are somewhat complex, result in the transfer of some oxygen from the peroxide to the spongy lead. (Some lead sulphate is also formed on both plates.) The surfaces of the plates are now in a similar condition (PbO), and the cell will no longer give a current (Fig. 415).

The original state of the cell can, however, be restored by passing a current through it in the opposite to the first direction. This reverses the chemical reactions, and the active surfaces again become spongy lead and lead peroxide. This is called *charging* the cell. Such cells are called secondary cells, because they must first be charged. They are also called storage cells because they store chemical energy and re-transform it into the energy of a current.

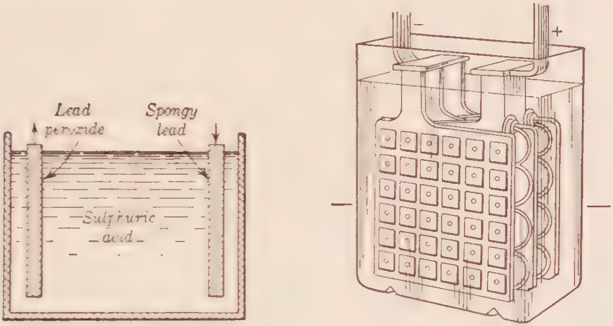


FIG. 415*a*. FIG. 415*b*.

Lead Storage Battery

The state of a cell can be tested by finding the density of the solution with a hydrometer; it becomes less dense as the cell is discharged and more dense as it is charged. Lead storage cells must not be left uncharged, or the plates will become covered with a white deposit of lead sulphate, which can be removed only with great difficulty. Too large a rate of discharge may cause "buckling" or disintegration of the plate (12 amperes per sq. ft. of opposed plate surface is safe).

In the charging of the cell SO_4^{--} ions and H^+ ions, due to the decomposition of the sulphuric acid (H_2SO_4), appear at the anode and cathode respectively. The chemical reactions at the plates may be written:

$$\text{At anode} \qquad PbSO_4 + SO_4^{--} + 2H_2O \rightleftarrows PbO_2 + 2H_2SO_4$$
$$\text{At cathode} \qquad PbSO_4 + 2H^+ \rightleftarrows Pb + H_2SO_4$$

These reactions are reversed in discharge. From these it will be seen why the concentration and density of the solution change.

What substances compose the plates in a lead storage cell? What is the electrolyte? What change takes place at each plate when the cell is discharging? Why does the current finally stop? How may the cell be recharged? What change in density of the electrolyte takes place during discharge? During charge? How may the state of charge of the cell be easily tested? Why should the cell not be left uncharged for a long time? Why is the cell called a secondary cell? What is the danger from too rapid discharge?

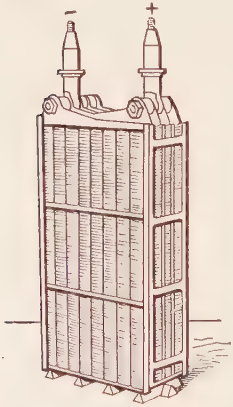


FIG. 416. Edison Storage Battery

455. The Edison Storage Cell.—In the Edison storage cell the plates are of iron and nickel peroxide (NiO_2), and the electrolyte is a solution of caustic potash (KOH). The active materials are held in small perforated boxes pressed into nickel-plated steel grids. While it has a lower e.m.f. and a higher internal resistance and is more costly than the lead storage cell, the Edison cell will stand discharged without injury, provided the electrolyte remains in the cell, and it is not so readily injured by over-discharge or rough usage (Fig. 416).

What are the electrodes in the Edison cell? What is the electrolyte? What are the advantages of the cell over the lead cell? The disadvantages?

EXERCISES

1. Sketch and explain the apparatus used for the electrolysis of water.

2. Draw a diagram of the apparatus used for electroplating. Label the parts and state whether the article to be plated is to be attached to the negative or to the positive pole.

3. Mention some practical applications of electrolysis and describe one in detail.

4. State the laws of electrolysis.

5. What is the difference in principle between the storage and the primary battery?

6. Give briefly the explanation of the operation of an Edison storage battery. For what class of work is this cell particularly valuable?

7. State what happens when a lead storage battery is charged and discharged. Why does the specific gravity of the electrolyte change on charge?

8. What are the principal electrical characteristics of the storage cell? (Voltage, current strength, internal resistance.)

9. What are the principal precautions to take in using a storage cell?

10. Silver cups are sometimes gold lined by electrolysis. Sketch a suitable apparatus and mark the poles.

11. The two ends of copper wires coming from a generator were dipped into copper sulphate. One turned dark. Was it the positive or the negative pole? Explain.

PROBLEMS

1. How long will it take a current of 3 amperes to deposit 10 grams of silver from a solution of silver nitrate?

2. A cup which had been immersed in a silver plating bath for 80 minutes was found to have gained 15 grams in weight. What was the current strength?

3. The increase in the weight of the copper plate of a Daniell cell was 600 grams. Assuming that the cell had delivered 0.10 ampere continuously, how long had the cell been in operation?

CHAPTER L

HEATING EFFECT OF THE CURRENT

456. Heat Produced from Electric Energy.—When a sufficiently powerful battery of voltaic cells has its terminals connected by a fine iron wire, sufficient heat is produced in the wire to make it glow, or even to melt it. When wires of different metals, but all having the same length and diameter, are connected in series across the poles of a battery, it is found that different amounts of heat are produced in the different wires. For example, when a copper wire and an iron wire of the same dimensions are used in series, the iron will become quite hot, while the copper wire will remain cool.

The difference between the action of any two wires in such an experiment evidently depends on their resistances. Joule showed by experiments like the above that, when a current passes through a conductor, *the number of heat units generated is proportional to:*

(a) The resistance of the conductor.
(b) The square of the current strength.
(c) The length of time the current flows.

If R is the resistance in ohms, I the current in amperes, t the time in seconds, and H the heat in calories, then:

$$H = 0.24 I^2 R t.$$

This conversion of electric energy into heat is a source of loss in transmitting currents. The so-called "I^2R loss" is diminished by using large wires, but the cost of these is heavy. It has been calculated that the most economical size of wire is such that the fixed charges (interest, taxes, etc.) equals the cost of the I^2R loss.

How could you show that an electric current produces heat? What three factors determine the amount of heat produced? State the formula for the heat produced. Is this heating effect always useful? How may the energy lost in heat be reduced?

457. Household Heating Appliances.—A convenient method of operating flatirons, coffee percolators, toasters, etc., is to use the heating effect of the current. A wire composed of an alloy of nickel and chromium has a high resistance (700 ohms per mil ft.), withstands oxidation well, and has a high fusing point. This wire is wound on an insulating base and forms the *resistor* of such appliances. The only disadvantage of these appliances is their high cost of operation. (Fig. 417.)

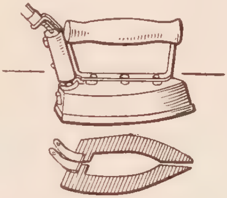


FIG. 417. Electric Flat Iron

Mention several household appliances employing electricity for heating. Why is an alloy used in these? Why are not such heating devices more commonly used?

458. Fuses.—Accidents may cause the passage of so heavy a current through some electrical appliance that it would become a source of fire danger, due to the intense heat. To prevent this, it is customary to place in every electric circuit a piece of easily fusible wire, of such a size that an excessive current melts it (Fig. 418). Such a *fuse wire* is generally enclosed in a case of some kind, so that the molten particles of metal will not be thrown about. In large installations a *circuit-breaker* auto-

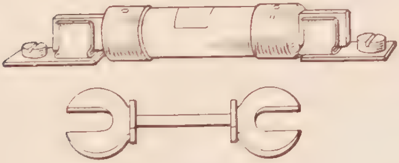


FIG. 418. Electric Fuses

matically opens the circuit whenever the current becomes excessive.

What is a fuse? Why are fuses used? How are they made? What is a circuit-breaker?

459. Electric Furnaces.—These are furnaces capable of producing temperatures up to 3500° C., while the ordinary metallurgical gas furnace reaches only about 2000° C. They are divided into two classes, *resistance furnaces* and *arc furnaces*. In the former the heat is produced by passing a heavy current through a resistance. These are used for making carborundum and artificial graphite. In the *arc furnace* huge electric arcs supply the heat. (Figs. 419-420.)

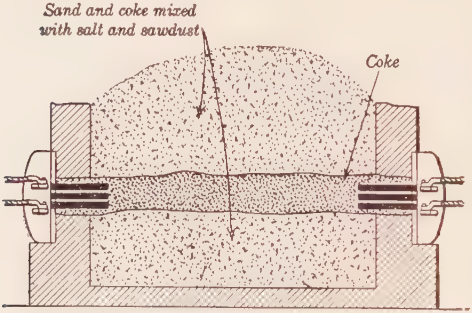


FIG. 419. Electric Furnace for Making Carborundum

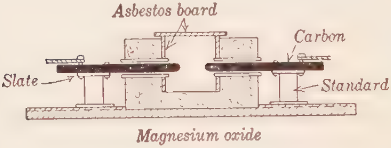


FIG. 420. Arc Electric Furnace

Mention two classes of electric furnace. What are their uses?

460. Electric Welding.—By pressing two pieces of metal together, and passing a heavy current through the junction, enough heat is developed to weld the two together. This process is used in welding pipes and bars. (Fig. 421.)

How is electric welding accomplished?

461. Arc Lights.—Sir Humphrey Davy was the first to show a real arc light. In 1808 in London he arranged 2000 cells so as to form one huge battery, and passed the current from this through two pieces of charcoal. When they were slowly separated, a dazzling arc appeared between them. It was not, however, until the invention of the dynamo that the arc light was commercially possible, but in 1880 it was used for street lighting, and has been in common use since that time.

To cause an electric arc to start, it is first necessary to press two pieces of carbon lightly together. The resistance at the point of juncture will cause heat enough to vaporize some of the carbon. If the points are then separated somewhat, the current will continue to flow across the ends through the carbon vapor, forming an *arc*.

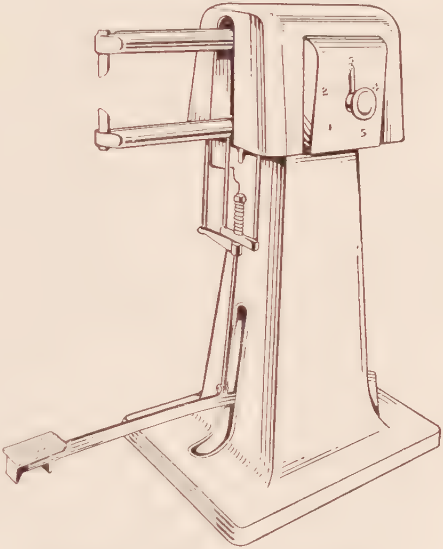


Fig. 421 Spot Welding Machine

As the carbons are gradually consumed, a crater forms on the positive carbon, while the negative carbon becomes cone shaped. (Fig. 422*a*.) Most of the light comes from the positive crater, which has a temperature of 3700° C., the highest temperature we have as yet produced. The arc light is now mainly used for searchlights, spotlights, and moving picture machines.

462. Incandescent Lamps.—The first incandescent lamps were thin filaments of platinum heated to incandescence by the passing of currents through them. Edison replaced the metal by a carbon filament, sealed in an exhausted globe, so that the carbon could not burn up when heated. The long slender carbon filament was produced by heating a cotton thread out of contact with the air.

The modern lamp is a fine filament drawn from the metal tungsten. The wire in an ordinary 10 watt lamp is only about ¾ mils in diameter. Such lamps use only about ⅓ as much energy as the old carbon filament for the same candle-power and give a much whiter light.

The globe of the incandescent lamp, instead of being exhausted, is sometimes filled with a gas that does not support combustion, such as nitrogen and argon. Such gas filled lamps, especially in large sizes, require only 1 watt for each candle power.

What was the conductor in the first incandescent lamps? What change did Edison make in this conductor? Why was the globe exhausted of air? Of what is the filament now usually composed? Are all the modern globes exhausted of gas? What advantages has the tungsten lamp over the carbon lamp? What is the advantage of the gas filled lamp?

How did Sir Humphrey Davy make the first electric light? Why did they not come into immediate use? In what form are they now used?

What must be done to start an arc lamp? Why does the current flow after the points are separated?

463. The Cooper-Hewitt Mercury Arc Lamp.—This is a greatly extended arc, in mercury vapor. The lamp consists of a slanting glass tube several feet long, having an iron plate at the upper end that serves as the negative electrode, and a pool of mercury at the lower end that forms the positive electrode (Fig. 422*b*). The tube is exhausted so that before the lamp starts to burn the almost perfect vacuum prevents the passage of the current.

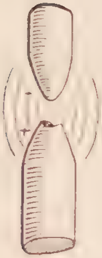


FIG. 422*a*. Arc Light Carbons

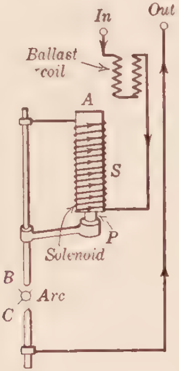


FIG. 422*c*. Feeding Mechanism of Arc Lamp

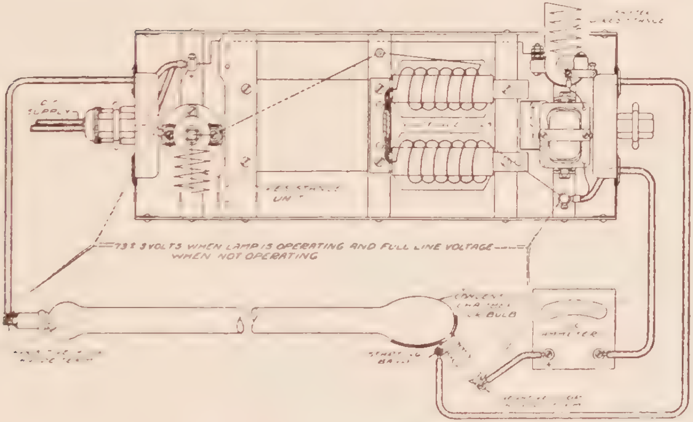

SUPPLY
73 ± 3 VOLTS WHEN LAMP IS OPERATING AND FULL LINE VOLTAGE WHEN NOT OPERATING
BULB

FIG. 422*b*. Cooper-Hewitt Lamp

To start the lamp the tube is tipped, and then lowered to its original position. The current passes through the momentarily continuous mercury path, and as this is broken the vaporized mercury forms a luminous arc from electrode to electrode.

The light is rich in actinic rays, but contains almost no red light. It is used extensively in photography, but not for ordinary lighting, as because of the absence of red rays it changes the color of objects. By making the tube of quartz the lamp becomes a powerful source of ultra-violet light.

Explain the construction of a Cooper-Hewitt lamp. What are its advantages? Its disadvantages? How can it be made to give ultra-violet light?

464. Arc Lamp Mechanism.—In commercial lamps some device must be used that will do two things, first, "strike the arc," that is, separate the carbons when the current is turned on, and, second, keep the distance between the two carbons the same in spite of their slowly burning away. In addition to the feeding mechanism, the lamp has a **ballasting resistance** to control the changes in the current, due to slightly varying voltage. (Fig. 422*c*.)

For a single arc light on a constant voltage line the lower carbon is fixed. The upper carbon is fastened to the end of a rod that passes through the regulating coil. At the upper end of the rod is a friction clutch. When the current is not passing, the upper carbon drops down and touches the lower carbon. When the current is turned on, the regulating coil lifts the rod, thus separating the carbons. As the carbons burn away, the resistance of the arc increases, and the current therefore decreases. The regulating coil then allows the upper carbon to drop, and the process is repeated. Such lamps usually burn for 12 hours or more before requiring new carbons.

What is meant by striking the arc? Why is it necessary to feed the carbons together while burning? How is the striking accomplished? The feeding? What is the object of the ballasting resistance?

465. Other Arc Lamps.—The arc will burn in a fairly tightly enclosed globe, and under these conditions the carbons last about

100 hours. Such an **enclosed lamp** also gives a steadier light than the **open arc.**

In the **flaming arc lamps** the carbons used are impregnated with chemicals, which, when vaporized in the arc, are very luminous. For example, calcium compounds give a dazzling yellow light. The high cost of the carbons and the expense of cleaning have prevented their general use.

The **metallic electrode lamp** uses for the positive electrode a block of copper, and for the negative electrode a thin iron tube, filled with powdered magnetite and oxides of chromium and titanium. This type of lamp is used for outdoor lighting only.

EFFICIENCY OF ELECTRIC LAMPS

Name of lamp	Watts for 1 candle power
Carbon filament	3—4
Metallized carbon	2.5
Tungsten	1.5
Gas filled	1.
Open arc	0.5—0.8
Flaming arc	0.4

What is an enclosed arc lamp? What are its advantages? What is a flaming arc? What are its advantages and disadvantages? What is a metallic electrode lamp? What is the composition of the electrodes? What type of lamp is most efficient?

466. Thermoelectric Currents.—In 1822 Seebeck, in making some experiments with a circuit of copper and bismuth in series with a galvanometer, chanced to hold one junction in his hand so that it was heated. He noticed that the galvanometer needle moved, showing the production of a current. This led to the thermoelectric method of producing currents, namely, **by the heating of one junction of a circuit consisting of two dissimilar metals, while the other junction is kept cold.** The current so produced is very small. It can, however, be greatly increased by using a number of such generators in series. In *thermoelectric cells* and *thermo-generators* a large number of strips of two different metals, usually bismuth and antimony, are arranged alternately in a series, and alternate junctions are heated, the intermediate ones being kept cool (Fig. 423*a*). Generators of this type are sometimes used commercially to produce currents of several amperes. A practical application of such currents is made in the pyrometer. A thermocouple is placed in a furnace, the temperature of which we wish to know. The current produced depends upon the temperature and is measured by a galvanometer, the scale of which is calibrated in degrees.

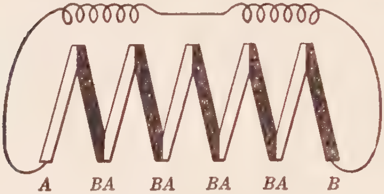


FIG. 423*a*. Thermo-Couple

How was Seebeck led to discover thermoelectric currents? How are they produced? What is a thermo couple?

467. Hot Wire Ammeters.—In these instruments a thin wire *W* is stretched horizontally. The sag is taken up by a wire *A*, which, in turn, is pulled sideways by a spring *S* and a thread *T*. This thread passes over a roller *R*, on which is mounted a pointer *P*. The current passing through *W* heats it, and it expands. Expansion causes it to sag. This sag is taken up by the spring, which pulls the thread *T* further to the right. This moves the cord passing over the roller, the roller rotates, and the pointer moves over the scale (Fig. 423*b*).

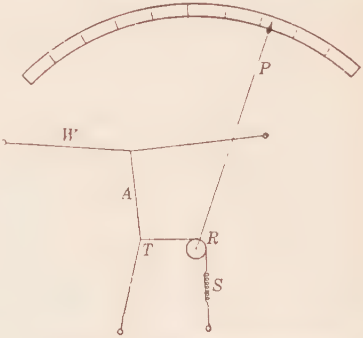


FIG. 423*b*. Hot Wire Ammeter

The scale is *calibrated* (has the divisions marked on it) by passing a known current, of say one ampere, through the

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ammeter, and marking the point where the pointer comes to rest 1. By repeating this with various known currents the scale is marked out. These ammeters can be used for either direct currents or alternating currents, since the heating effect is independent of the direction of the current.

Can the heating effect be used as a basis for measuring an electric current? Describe a hot wire ammeter. How is the slack in the wire taken up? What makes the pointer move? How is the instrument calibrated? Why is this necessary? What advantage has a hot wire ammeter over a magnetic meter?

EXERCISES

1. State the laws governing the evolution of heat in an electric circuit.

2. State the formula for calculating the heat developed.

3. Mention several practical applications of electrical heating.

4. How is the heating tendency of an electrical circuit used to safeguard electrical installations?

5. In a house where there were a number of electrical appliances it was found that they frequently blew the 5 ampere fuses in the fuse block. 20 ampere fuses were substituted and this cured the trouble. Was this substitution wise? If not show the danger by actual figures.

6. Sketch the resistor in a flat iron.

7. Sketch and describe the operation of an electric furnace.

8. Sketch, describe and explain the operation of an incandescent lamp.

9. State some of the characteristics of a conductor suitable for the filament of an incandescent lamp.

10. Sketch, describe and explain the operation of an arc lamp.

PROBLEMS

1. What is a 110 volt lamp? The current supply to a trolley is at 550 volts. How can 110 volt lamps be used in a trolley car?

2. A 60 watt, 120 volt lamp uses about ½ ampere. A dry cell on short circuit will give 30 amperes. Will the dry cell light the lamp? Explain.

3. What is the source of heat in an electrical heating pad? How is the heat controlled?

4. What is the cause of the sparks seen as the trolley wheel runs along a trolley wire? Why are they often very bright on wet or frosty nights?

5. Sketch and explain the operation of a hot wire ammeter.

Fig. 424. Michael Faraday explaining the first induction of currents

CHAPTER LI

ELECTROMAGNETIC INDUCTION

468. Faraday's Discoveries.—Michael Faraday discovered, in 1831, a new method of producing electric currents, and this method is used in generating the enormous currents used today. This discovery must be regarded as one of the most important ever made.

Place a coil of insulated wire on a table, and connect it with a galvanometer (Fig. 425). Thrust a magnet into the coil, with its north pole downward, and leave it there. The galvanometer will show that, *during the motion of the magnet, there is a momentary current induced in the circuit, but there is no current when the magnet is at rest in the coil.*

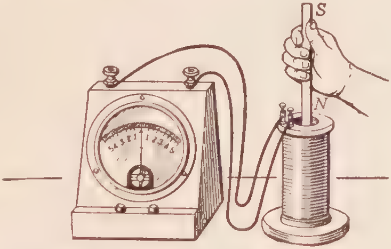

FIG. 425. Current Induced by Moving Magnet

Now withdraw the magnet. Again there will be a momentary current during the motion of the magnet, but the direction of this current, as is shown by the direction of deflection of the galvanometer needle, will be opposite to that of the first.

Similar momentary currents will be obtained by thrusting the south pole of the magnet into the coil, and on removing it. These will, however, differ in one important respect from the former ones. The current obtained by thrusting the south pole into the coil will be opposite to that produced by thrusting the north pole into the coil, and similarly as regards withdrawing the south pole.

Such momentary currents generated in a coil are called *induced currents.*

To find the direction in which the first of these momentary currents traversed the wire of the coil, open the switch at S (Fig. 426a), and insert a voltaic cell. The cell should be one that gives only a very weak current, so that the galvanometer shall not be injured. A copper wire and a zinc wire, held between the moistened thumb and finger, will suit. Connect it in such a way as to deflect the galvanometer needle in the direction in which it was deflected by the momentary current. The direction of the current in the coil will then be from the copper of the cell, through the wire, to the zinc. This gives the direction of the momentary current produced by the magnet. While this momentary current was passing along the wire of the coil, the coil had the properties of a magnet, and its north pole can be found by the rule stated in § 419. The *north pole* of this equivalent magnet was at the top of the coil (Fig. 425), so that it faced the approaching *north pole* of the magnet. Now consider the other experiments. When the north pole of the magnet was being withdrawn, the momentary current in the coil was in the opposite direction to the first one, so that the *south pole* of the coil was at the top. This was also the case when the south pole of the magnet was approaching the coil. But when the south pole of the magnet was receding, the *north pole* of the coil was at the top, as in the first experiment.

What was Faraday's most important contribution to the science of electricity? What happens when a magnet is thrust into a coil of wire connected to a galvanometer? How long does the effect last? What happens when the magnet is pulled out of the coil? How does the direction of the current in one case compare with its direction in the other? If the opposite pole of the magnet is used are the results the same? What are such currents called?

469. Induced E.M.F.—If the circuit of the coil in figure 426*a* is not closed, that is, if there is a gap in the circuit, there is no flow of electricity the whole way around the circuit. There is, however, a very brief dash of electrons toward one end of the wire, and there they are halted by the gap. The result is an excess of negative electricity at one end of the wire, leaving an excess of positive at the other end. The difference of potential between the ends of the wire is an e.m.f., which lasts while the magnet is in motion. This would cause a current if the gap were bridged. Thus we see that when the circuit is complete, the approach of the magnet causes an e.m.f. in the circuit. In considering the applications of induced currents, we can reason more clearly if we first consider the induced e.m.f.'s, and then regard these as causing the currents.

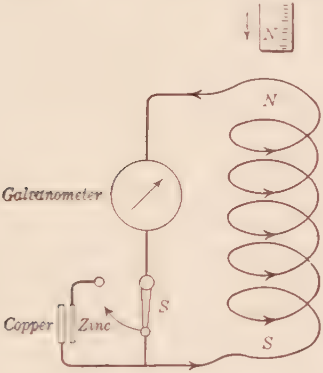

FIG. 426*a*.

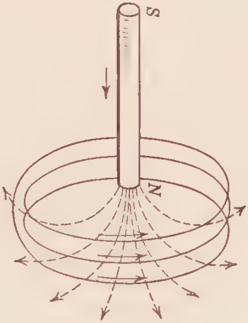

FIG. 426*b*.

Direction of Induced Current

If we repeat the experiments of § 468, but move the magnet *very slowly*, we shall find that the induced currents, though they last longer, are very much weaker. Evidently, then, *the* *magnitude of the induced e.m.f. depends on the speed at which the magnet is moved toward or away from the coil.*

When the north pole of a magnet is thrust into a coil what is produced? Upon what does the magnitude of the induced e.m.f. depend?

470. Laws of Electromagnetic Induction.—Faraday devised a simple way of describing the results of the preceding experiments and of others that we shall describe presently. He regarded the induction as due to the lines of force of the magnet, or the magnetic lines, as we may call them. The total number of magnetic lines passing through, or enclosed by, a circuit is also called the *magnetic flux* through the circuit.

When the magnet was held above the coil (Fig. 426*b*), with its north pole downward, only a few of its lines passed through the coil. When it was being thrust into the coil, more and more of its lines passed through the coil. We may say, then, that there was an induced e.m.f. as long as the magnetic flux through the coil kept increasing. There was another induced e.m.f. while the magnet was being withdrawn, that is, while the magnetic flux through the coil kept decreasing. The following are *Faraday's laws of induction:*

1. While the magnetic flux through a coil is increasing, there is an induced e.m.f. in the coil. When the flux is decreasing, there is an induced e.m.f. in the opposite direction.

2. The induced e.m.f. is proportional to the rate of change of the magnetic flux through the coil.

The rule stated in the following section will tell us which of the two possible directions through a coil is the *direction* of the induced e.m.f. in any particular case.

What is meant by an induced e.m.f.? Upon what does the induced e.m.f. depend?

471. Direction of Induced E.M.F.—In the experiments of § 468, when the north pole of the magnet was brought down toward the coil, the upper end of the coil acted like a north pole and *opposed* the downward motion of the magnet. When the magnet was being removed from the coil, the upper end of the coil was a south pole, and this *opposed* the upward motion of the magnet. In the other cases also the action of the coil was to oppose the motion of the magnet which caused the induced currents. In these cases and others to be considered, **an induced current is in such a direction as to oppose the action that induces it.** This is called **Lenz's law.**

In the experiments already considered the *action* that induced a current was the motion of a magnet. We shall see that there are other forms of action that give rise to induced currents.

What is the cause of the induced e.m.f.? State Faraday's laws of induction. State Lenz's law.

472. Induction of Currents by Currents.—Let us now replace the magnet heretofore used by a coil in which a current from a battery is flowing (Fig. 427*a*). Such a coil has magnetic lines of force and is equivalent to a magnet. By applying the rule of § 419, you can connect the battery to the coil in such a way that the north pole of the coil is downward. You will now find, as might be expected, that whenever the upper coil (Fig. 427*a*) is moved toward or away from the lower coil, temporary currents are induced in the lower coil, just as if the upper coil were a real magnet. The coil in which the inducing current flows is called the *primary coil,* and the current in it is called the *primary current.* The coil in which currents are induced is called the *secondary coil,* and the induced currents are called *secondary currents.*

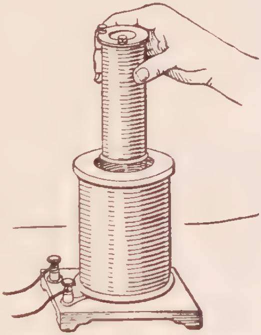

FIG. 427*a*. A Current Inducing a Current

Secondary currents can also be induced by leaving the primary coil at rest in the secondary and *changing the primary current in any way.* The following experiment will illustrate this. First, hold the primary coil, without a current, above the secondary, and make a current in the primary by closing a switch; the galvanometer will show a momentary secondary current. Next, plunge the primary coil into the secondary; there will be another momentary current in the *same* direction as before. Finally increase the primary current, without breaking the circuit, by reducing the resistance in the circuit; there will be a third induced current in the *same* direction as the other two. Thus, making or increasing the primary current produces a secondary current in the same direction as when the primary coil, carrying a current, is lowered into the secondary coil. The effect of decreasing or breaking the primary current can be found by reversing the preceding steps. You will readily see how these results could have been inferred from Faraday's first law.

The direction of the secondary current, when the primary current is changing in any way, can be found from Lenz's law. When the primary current is made, it produces magnetic lines inside the coils. The direction of the secondary current is such that the magnetic lines due to it are opposed to those of the primary current. It is evident, therefore, that *the secondary current at make of the primary is opposite in direction to the primary current.* At break of the primary current its magnetic lines would disappear, but the secondary current is now in such a direction that its magnetic lines *oppose* the disappearance of the field, that is, they are in the same direction as the lines of the primary current. Hence *at break of the primary current the secondary current is in the direction in which the primary current was.*

Can currents be induced without the use of magnets? Explain how one coil may be made to affect another. What is a primary coil?

A secondary coil? Can the coils be kept stationary and yet induction take place? If a current is sent through the primary in a clockwise direction, what is the direction of the induced secondary current?

473. E.M.F. Due to Cutting Lines of Force.—When the number of lines of force through a circuit is increasing, owing to the approach of a north pole (Fig. 425), the lines of force, in getting into the circuit, must cut across a conductor that forms part of the circuit. The same is true if the magnet is at rest and the circuit is made to approach the magnet, except that now it is the conductor that moves. But in both cases the conductor is moving relatively to the lines of force, and in such cases it is only the *relative motion* that counts. Now it is often convenient to regard the e.m.f. and the current induced in a wire as due to the wire *cutting across the lines of force.* The simplest case of this is represented in figure 427*b*. A straight wire *AB*, connected to a galvanometer, is supposed to be moving down across the lines of force of a strong horseshoe magnet (or, better, electromagnet). An e.m.f. is induced in the circuit, and in *AB* it is in the direction from *A* to *B*. If *AB* were moving upward, the induced e.m.f. would be from *B* to *A*. In all such cases the direction of the induced current and the induced electromotive force can be found by the following rule, called the **right hand rule,** or dynamo rule:

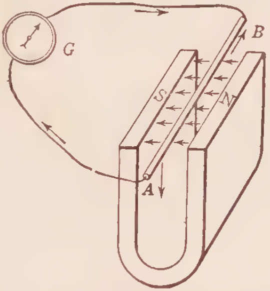

FIG. 427*b*. E.M.F. Due to Cutting Lines of Force

Hold the thumb, the forefinger, and the center finger of the *right hand* at right angles, as indicated in figure 427*c*. *If the* **f***orefinger is pointed in the direction of the lines of* **f***orce, and the thu***m***b in the direction of the* **m***otion of the wire, the* **c***enter finger will point in the direction of the induced* **c***urrent and* *e.m.f.* To remember this rule, note the repetition of the letters **f f, m m, c c.**

If you apply this rule to one of the experiments in § 468 you will find that it gives a correct result.

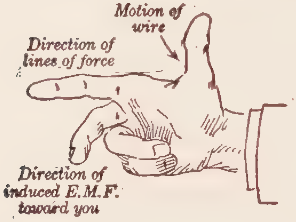
Motion of wire
Direction of lines of force
Direction of induced E.M.F. toward you

FIG. 427*c*. Right Hand Rule or Dynamo Rule

When a magnet is brought up to a coil does the induced current tend to assist or oppose the motion? How does this take place? What action does the magnetic field of the secondary have on the magnetic field of the primary? State Lenz's law.

474. Self-Induction.—Connect three dry cells in series. Fasten to one free pole a copper wire, and to the other an iron wire. Wind the end of the copper wire around the clean end of a file, so as to make a good electrical contact, and then draw the end of the iron wire quickly over the file. A few small sparks will be seen.

Now introduce an electromagnet into the circuit, and repeat the experiment. Many more, and much larger, sparks will be seen.

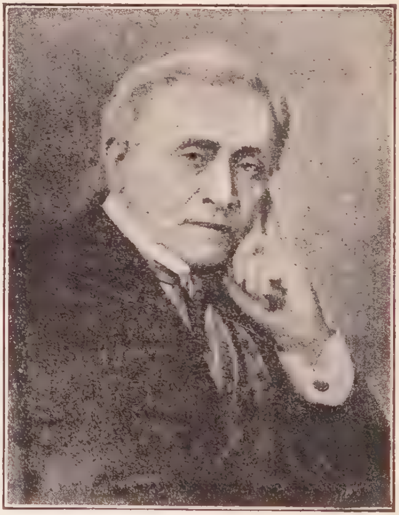

FIG. 428. Joseph Henry

This effect was discovered by Joseph Henry and is another case of induced currents. Imagine a wire wound around an iron bar (Fig. 429*a*). As soon as a current *starts* to flow through each coil, a magnetic field is set up in the remaining coils, and this induces an e.m.f. that tends to oppose the original current. The effect is such that the current does not immediately reach the value that it should have according to Ohm's law. On breaking the current a reverse action takes place. The decreasing magnetic field generates an opposing e.m.f., and this tends to prolong the current. If the coil has a large number of turns and is wound on an iron core to concentrate the magnetic field, this induced e.m.f. will have a high enough potential to give a spark over a short distance. This is called the **electromotive force of self-induction.** Remember that **self-induction only occurs when the current is changing.**

When an electric circuit is broken, what happens at the break? What is the effect of adding an electromagnet to the circuit and then breaking the circuit? Who discovered this effect? How does the magnetic effect of a current react on the growth of the current? On the decrease of the current? Why does the current tend to keep on flowing when the circuit is broken? Define electromotive force of self-induction.

475. Applications of Self-Induction.—One use made of self-induction is the *make-and-break ignition* sometimes used on gas engines (Fig. 429*a*). A spark coil *S* is connected in series with a battery *B* and a make-and-break contact *C* in the head of the engine cylinder *E*. This contact has one stationary point *A* and one moving point *D*, so arranged that they separate when the gas charge is to be exploded. The separation breaks the circuit, and the induced current has a sufficiently high e.m.f. to cause a spark to jump the air gap, thus exploding the charge.

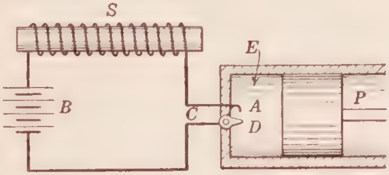

Fig. 429*a*. Make-and-Break Ignition

What use is made of self-induction? How is the make-and-break accomplished?

476. Induction Coils.—An induction coil is used to transform a low e.m.f. into a high e.m.f. It has a **primary coil** *P* (Fig. 429*b*) of a few turns of heavy insulated wire wound around an **iron core** *I*. The core consists of a large number of iron wires, so as to avoid the production in it of induced or eddy currents. Around the primary coil is the **secondary coil** *S* consisting of a great many turns of very fine insulated wire. To guard against the insulation breaking down, both coils are filled with some insulating material. The **circuit-breaker** *AD* is in the primary circuit, and is an automatic device for making and breaking the circuit, similar to that used in the electric call bell (§ 421). In the base of the coil is a **condenser** *C*, its terminals being connected in the primary circuit, one on each side of the circuit breaker.

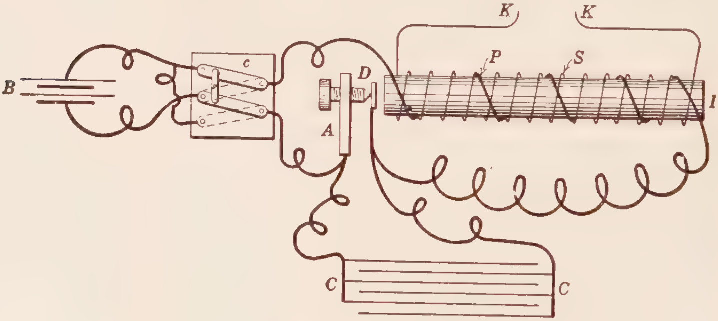

FIG. 429*b*. Induction Coil

When the primary of an induction coil is connected to a battery *B* and the circuit is closed, the circuit-breaker makes and breaks the circuit many times a minute. This generates in the secondary coil an induced current of such high e.m.f. that sparks pass between *K*-*K*, the terminals of the secondary coil. Such a coil has been constructed with many miles of wire in the secondary, and capable of producing a spark 40 inches long.

The condenser aids the action in two ways. First it gives a large capacity to the primary coil, so that, when the circuit is broken, the difference of potential between the contact points of the circuit-breaker is not great enough to produce a spark at the air-gap. The break is therefore more sudden, and the induced e.m.f. is therefore higher. Second, after the break, the condenser discharges back through the coil. This reverse current aids in demagnetizing the core, which again results in increasing the induced e.m.f. because it increases the rate of change of the magnetic field.

The discharge from a large coil, taken through the body, is dangerous. Great care should be used in the handling of such coils.

What is an induction coil? What size of wire is used in the primary? In the secondary? Which has more turns? Why? Why is the core made of iron wires instead of one solid piece? What is the purpose of the circuit breaker? Explain how the coil is operated. What does the length of the spark produced depend upon? What two purposes are served by the condenser? Why should care be used in working with an induction coil?

EXERCISES

1. What is the fundamental principle involved in the production of electricity on a commercial scale?

2. How is the principle mentioned above used? Why is this method superior to the chemical method of producing current?

3. What are the essential features of the apparatus necessary to produce a current by induction?

4. Having a coil of wire and a magnet, how can you produce a current? Does the current, once started, continue to flow? Under what conditions does it cease to flow?

5. Using a coil of wire and a magnet, how would you generate a current in the positive direction? State the law.

6. What effect does changing the pole which is plunged into the coil, have upon the direction of the current?

7. What is the relation of the direction of the current produced by plunging a magnet into a coil to that of the direction of the current produced when the magnet is withdrawn?

8. What do we believe is the actual cause of the current produced by plunging a magnet into a coil?

9. State Faraday's laws of electromagnetic induction.

10. Is it possible to substitute anything for the magnet referred to in the previous questions and still produce a current in the coil?

11. What is a primary coil? A secondary coil?

12. Having two separate and insulated coils of wire, one within or near the other, is it possible to produce a current in one of them by doing something to the other? How can this be done? State in detail the conditions necessary and the results.

13. State Lenz's law.

14. Explain self-induction. Illustrate by a practical application.

15. Sketch, describe and explain an induction coil.

16. What is the function of the condenser in an induction coil? Where is it placed? Where is it connected?

17. Mention several applications of the induction coil.

18. Draw a diagram showing just how the induction coil is connected in the ignition system of an automobile.

19. What important difference is there between the method of operating a coil on a Ford engine and that used on most other automobiles?

20. What sort of coil is used on the ordinary make-and-break engine? How is the coil connected?

CHAPTER LII

DYNAMOS AND MOTORS

Direct Currents

477. A Simple Dynamo.—A dynamo is a machine for converting mechanical energy into electrical energy. Dynamos are made in many different forms for different purposes, but the fundamental principle is the same in all, namely, **the induction of a current in a coil of wire by a changing magnetic flux through the coil.**

Connect a single loop of wire by long wires to a galvanometer, and place the loop in a magnetic field with the plane of the loop at right angles to the lines of force (Fig. 430). In this position a certain number of lines of force pass through the coil or "thread" the coil, as it is sometimes expressed. Now rotate the loop in the direction of the arrow. As it turns, fewer and fewer lines pass through it. When it has turned through 90°, it is parallel to the lines, and there is practically no flux through it. During this quarter turn the number of lines of force that pass through the loop is continually *decreasing,* and there is therefore an induced current in the loop and in the external circuit. As the rotation is continued through an-

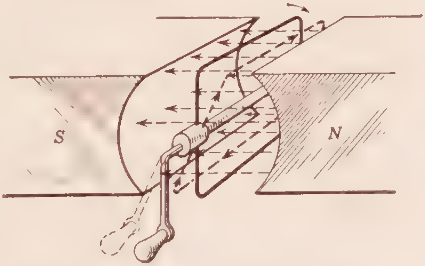

Fig. 430. Simple Ideal Dynamo

other 90°, the flux through the loop is continually *increasing,* but the lines of force now pass in the opposite direction through the loop. The effect of the two reversals is that the current is not reversed. Thus in the half turn the current is always in the same direction.

In the second half turn there is also an induced current that is always in the same direction, but this is the opposite of the direction of the current in the first half, since the flux through the loop is in the opposite direction. Thus we see that in every complete revolution of the loop there will be a current in one direction during one half of the revolution, and a current in the opposite direction during the other half, the current reversing at the beginning and end of every half revolution. These reversals are shown by the galvanometer, if it is sufficiently sensitive.

What is a dynamo? What principle underlies its operation? Explain what happens when a single turn of wire is rotated between the poles of a magnet. Why is this effect produced? Why does the current not flow in the same direction during an entire rotation of the coil? How many times during the rotation does the current reverse? At what positions of the coil do the reversals take place?

478. Strength and Character of the Induced E.M.F.— Imagine the loop in a vertical position, and then rotated 5°. Only a slight change in the number of lines of force through it will occur. Imagine the loop in a horizontal position, and then rotated 5°. A large change in the number of lines of force through it will occur. Since the induced e.m.f. depends on **the rate of change** of the magnetic flux passing through the coil, the e.m.f. must steadily increase during the first quarter turn. An inspection of figure 430 will show that during the second quarter turn the e.m.f. will steadily decrease, during the third quarter turn increase, and during the fourth quarter turn decrease.

Such a simple generator as we have been describing produces *an alternating c.m.f.* and generates *an alternating current.*

Is the e.m.f induced the same at every position of the coil? Where is it a maximum? Why? What name is given to the current delivered by such a generator?

479. Magnetos.—By using a coil of many turns, wound on an iron core to strengthen the magnetic field, and by placing this coil between the poles of a permanent magnet, we obtain a generator, called a *magneto,* capable of producing a strong alternating current (Fig. 431). Magnetos are used to ring the call bells in small telephone installations, and in the ignition system of some automobiles. The rotating part, consisting of a coil, iron core, and connections, is called the *armature.* When you turn the crank on the outside of the telephone box, you rotate the armature, thus generating a current that rings the bell.

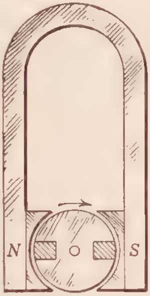

Fig. 431. Magneto

The ends of the wire of the coil are soldered to two *collecting rings* (Fig. 432*a*). To make good electrical contact between the outside circuit and the collecting rings, the wire is fastened to a piece of spring brass, called a *brush.* In many dynamos these brushes are made of carbon (graphite) and so mounted that a spring holds them against the rings.

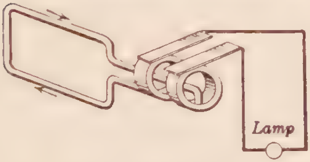

Fig. 432*a*. Collecting Rings

The generator built into the Ford engine is a magneto, in which the magnets move instead of the coils of wire. It makes, of course, no difference which moves, the essential thing being the rate of change of the lines of force passing through the coil. (Fig. 432*b*.)

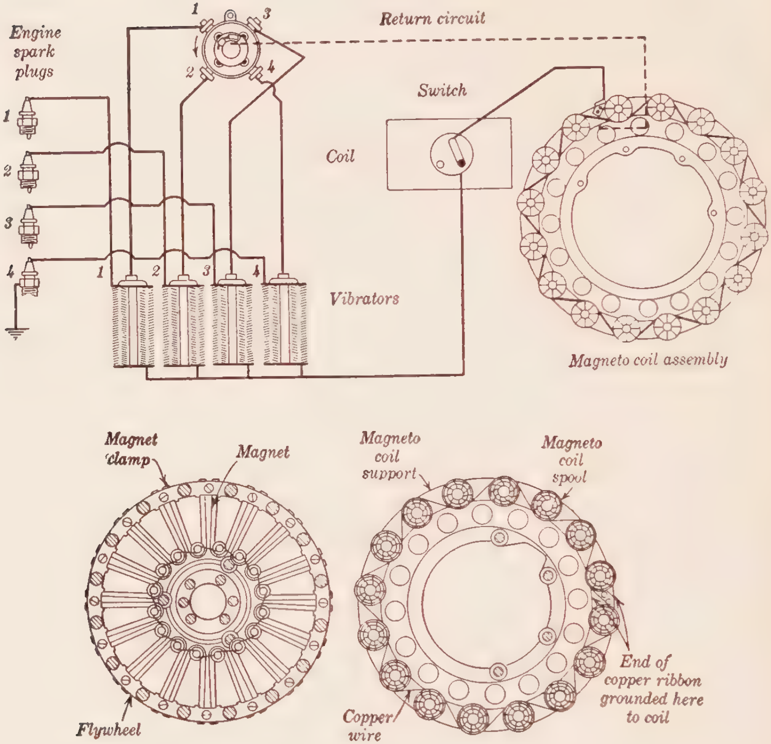

FIG. 432*b*. Ford Ignition System

What is a magneto? What use is made of the magneto? What is the armature? What are the collector rings? What is their purpose? What is the purpose of the brushes? Of what materials are they commonly made? Does it make any difference whether the armature or the magnets move? Why not?

480. The Commutator.—To convert the alternating current given by a simple generator into a direct or continuous current, we use a *commutator*. To understand its action, imagine the ends of our simple loop to be soldered to a split ring, as shown in figure 433. This split ring is a metal tube, sawed in halves and mounted on the end of the rotating shaft, so that there is no electrical contact between the two parts.

The external circuit is connected to two brushes that press on the two segments of the commutator. These brushes are so placed that, when the direction of the current in the coil reverses, the segment of the commutator on which the brush rests also changes. That is, starting with the loop vertical, during the first half turn a current is being induced, and this passes out from the segment (bar) A to the positive brush B. During the second half turn of the loop a current in the opposite direction is induced, and this passes from the segment C to positive brush B with which C is now in contact. Hence, in the external circuit, *the current is always in the same direction.* A commutator therefore converts a simple alternating generator into a direct current generator.

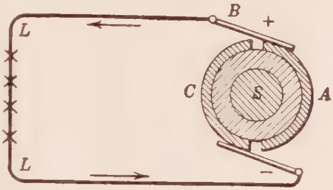

FIG. 433. The Commutator

What is a commutator? How is a simple commutator made? How does the commutator maintain a constant direction of current in the external circuit?

481. The Gramme Ring.—The simple direct current generator described in the last paragraph has the disadvantage that the current produced is pulsating. Twice during each revolution of the coil the e.m.f. sinks to zero, and twice rises to a maximum. The **Gramme ring** is an armature used to overcome this difficulty. The armature core is made of either iron wire, or thin iron disks placed at right angles to the axis of rotation. These are used instead of a solid core in order to prevent the formation of induced currents, *eddy currents,* in the core, as these waste energy. This core serves to carry the magnetic flux from one pole of the magnet to the other. Very few lines of force pass through the air space inside the core (Fig. 434). Around the core a number of coils of insulated wire are wound, all in one direction, and all joined electrically. The wire between the coils is connected to a commutator that has as many segments as there are coils in the armature.

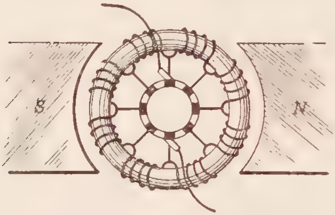

FIG. 434. Gramme Ring Armature

When the Gramme ring armature rotates, the flux through the coils is constantly changing. The wires on the *outside of the ring* cut lines of force, those on the *inside of the ring* do not, because there is no magnetic flux there. Moreover, the outside wires on the right-hand side of the ring are moving in such a direction as to generate an e.m.f. in a direction opposite to that generated in the outside wires on the left-hand side. When there is no outside connection, these two opposing e.m.f.'s neutralize each other.

When the external circuit is closed through a lamp or other resistance, the condition changes. A current then flows up both sides of the armature and out through the top brush to the external circuit. In this case the armature circuit is double, consisting of its two halves in parallel. The current through the armature has two paths, and one brush is always negative and one positive.

What is the disadvantage of a simple generator of one coil? How is the Gramme ring constructed to overcome this disadvantage? Why does it have a wire core? How many segments compose the commutator? What happens when the armature rotates? How does the direction of the current in one half of the armature correspond with that in the other half? If the two halves oppose each other, how can any current be delivered?

482. The Drum Armature.—It is difficult to wind the wire around the core of a Gramme ring, and, moreover, the wires on the inside of the ring contribute nothing to the current generated, since they cut no lines of force. Hence the Gramme ring has been superseded by the **drum armature** (Fig. 435). In this the core is made with slots cut lengthwise in the circumference, and the coils are wound in these slots. The active wires in one slot are connected across the end with the active wires in another slot, so that there are no wires that give no service on the inside of the core. By increasing the number of coils to twenty or more, a nearly steady current is produced.

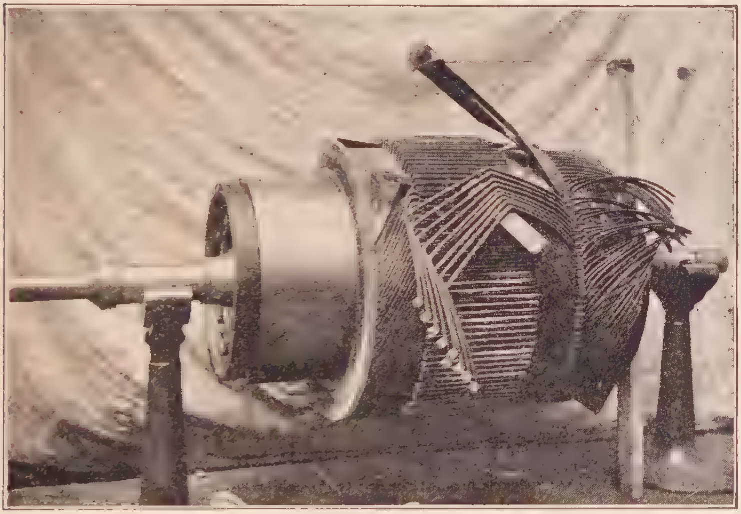

FIG. 435. Drum Armature of a 3000-volt D.C. Generator

Such drum armatures require a large number of commutator bars. These are fastened to the end of a shaft and insulated from each other by sheet mica. The ends of the coils are soldered to these bars.

What is a drum armature? What are its advantages over the Gramme ring? How are the coils connected to the commutator segments? How are the segments insulated from each other? What is the object of many coils on the armature of a generator?

483. Field Magnets.—The intense magnetic field required for the operation of dynamos is produced by electromagnets. Their poles are so shaped as to surround the armature as much as possible and leave only a small air gap. These expanded pole pieces are called the *pole shoes.*

The current necessary to excite these electromagnets is taken from the armature. There are three methods of winding employed, the choice depending on the use to be made of the generator. In every case there is enough residual magnetism in the iron core of the magnets to allow the generator to start producing a current, and the voltage gradually builds up. The three windings are:

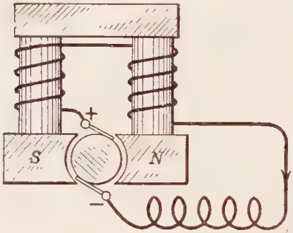

Fig. 436. Series Wound Dynamo

(1) *Series winding*, where all the current passes through a comparatively few turns of heavy wire wound on the iron core of the magnets (Fig. 436). In such generators the voltage rises as the load increases. They are used on constant current lines, for example, for arc lights in series.

(2) *Shunt winding*, where the main circuit divides and only a small part of the current passes through many turns of fine wire wound around the magnetic cores. They are used where only a fair voltage regulation is required. The voltage is nearly constant, and can be regulated by a field resistance (rheostat) (Fig. 437).

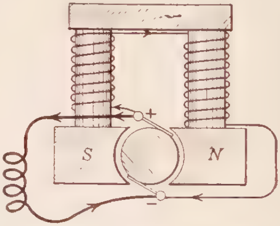

Fig. 437. Shunt Wound Dynamo

(3) *Compound winding*, where there is a combination of

the series and shunt windings (Fig. 438). This can be designed to give a constant voltage, and is much used to furnish current for lamps and motors that are connected in parallel and require a constant voltage.

How is the magnetic field of a generator produced? What is meant by a series winding? A shunt winding? A compound winding? Sketch each of these types of winding. What is accomplished by each type?

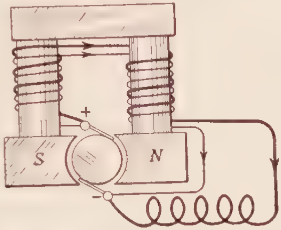

Fig. 438. Compound Wound Dynamo

484. Multipolar Generators.—The simple generators that we have been studying have had two poles and are called *bipolar machines*. Large generators usually have four, six, eight, or many poles, and are called *multipolar generators*. The armature of a four-pole generator cuts four sets of lines of force in each revolution, while the armature of a two-pole generator cuts only two sets. Because of this, a four-pole machine will give the same voltage as a two-pole machine when it is run at half the speed. A multipolar machine is cheaper to build because it requires less iron to carry the magnetic flux. (Fig. 439.)

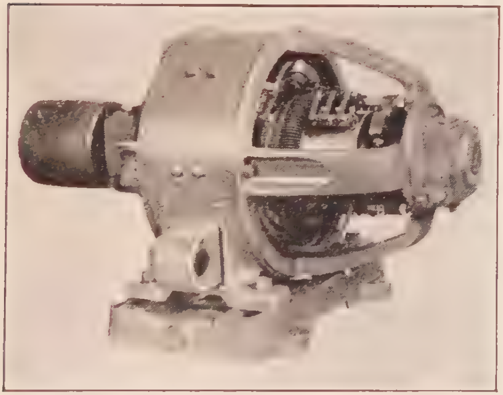

Fig. 439. Multipolar D.C. Generator

What is a bipolar generator? A multipolar? What is the advantage of a multipolar generator?

485. Electric Motors.—Imagine once more our loop of wire placed between the poles of a magnet (Fig. 440). Pass a current from an external source through the loop in the direction indicated by the arrow. In accordance with the facts stated in § 417, the magnetic field exerts a force on the wire and the loop will rotate, thus transforming the electrical energy of the current into mechanical energy of rotation. A motor is a generator reversed.

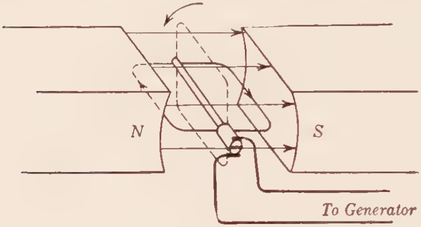

FIG. 440. Ideal Motor

Another simple way of explaining the rotation of a motor is to consider the armature as an electromagnet, the poles of which are alternately attracted and repelled by the field poles. The attraction is changed to a repulsion, at the proper time to produce continuous rotation, by the brushes sliding from one segment of the commutator to the next, thus reversing the direction of the current in the armature.

How does a motor differ from a generator? What causes a motor to operate?

486. Electric Power.—The unit of electric power, or rate of doing work, is the *watt,* named after James Watt, the inventor of the steam engine. One watt is the power produced by a current of one ampere flowing under a drop of potential of one volt.

$$\textbf{Watts} = \textbf{amperes} \times \textbf{volts}$$

The watt is too small a unit for many commercial purposes, and the *kilowatt,* which equals 1,000 watts, is then used. One horse-power equals 746 watts, or one kilowatt equals 1.34 horse-power. Since power is the rate at which work is done, the total work done in any time can be found by multiplying the power by the time. If an electric generator delivers energy at the rate of 12 kilowatts for 8 hours it does $12 \times 8 = 96$ *kilowatt-hours* of work.

We buy electrical energy by the kilowatt-hour. If the rate is 10 cents per kilowatt-hour and we use 6 lamps for 4 hours, each lamp taking 50 watts, our bill will be:

$$\frac{6 \times 4 \times 50 \times 10}{1{,}000} = \frac{12{,}000}{1{,}000} = 12 \text{ cents}$$

In laboratory work a smaller unit is sometimes desirable. This is the watt-second or *joule*. Work (joules) = current (amperes) × e.m.f. (volts) × time (seconds) or:

$$\mathbf{W} \textbf{ (joules)} = \mathbf{I} \times \mathbf{E} \times \mathbf{t}$$

Define the watt. How are watts computed? What is a kilowatt? How many watts make a horse power? How is the total work in an electric circuit computed? What is a kilowatt-hour? How is the cost of electric energy computed? What is a joule?

EXERCISES

1. What is the fundamental principle concerned in the operation of a dynamo?

2. What are the essential parts of a simple dynamo?

3. What is the relation between a dynamo and a motor? How may one be changed into the other?

4. Draw a diagram showing a simple dynamo and explain its operation.

5. Sketch and describe the operation of the commutator in a direct current dynamo.

6. What are the characteristics of the current which flows from a simple direct current dynamo?

7. What do you mean by a direct current? By an alternating current?

8. What is a magneto? How does the current obtained from a magneto compare with that from an ordinary dynamo?

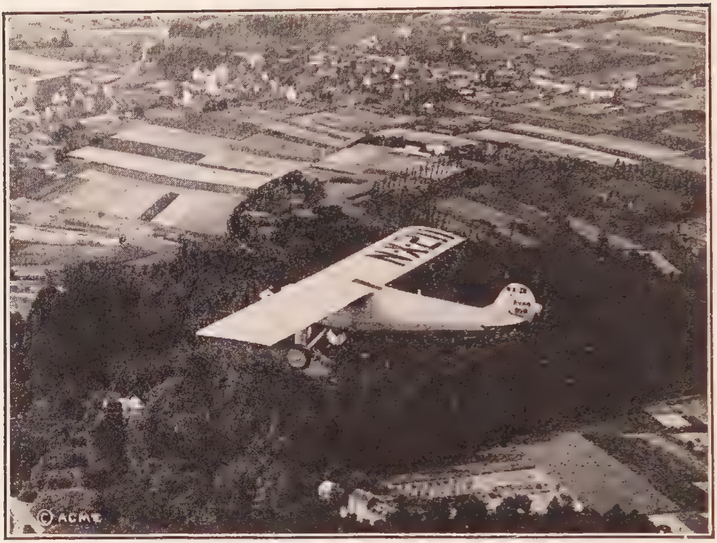

FIG. 441. Col. C. A. Lindbergh flying over Belgium in the "Spirit of St. Louis"

The **Earth Inductor Compass,** which guided Col. Lindbergh across the Atlantic, acts like a direct current dynamo. Its magnetic field is that of the earth. The brushes of the commutator can be shifted. For any desired course they are set so that no current is shown by a galvanometer in the circuit. If the airplane gets off the course set, the brushes are no longer in the neutral position, and the galvanometer is deflected, giving warning to the pilot. The coil is driven by a small windmill, the stem of which can be seen above the fuselage in the picture and in Fig. 120*b*.

9. What are the advantages and disadvantages of a magneto, compared with an ordinary dynamo?

10. Describe the Gramme ring. Why is it seldom used in commercial machines?

11. What is a drum armature, and what are its advantages?

12. Draw a diagram of a series wound dynamo, and give its characteristics and uses.

13. Draw a diagram of a shunt wound dynamo, and give its characteristics and uses.

14. Draw a diagram of a compound wound dynamo, and give its characteristics and uses.

15. Sketch, describe and explain the direct current motor.

16. What is the unit of electric power?

PROBLEMS

1. A man bought an electric heater which required 9 amperes at 110 volts, to heat his garage. How much would it cost to run it 10 hours each night, for a month of 30 days, at 10 cents per kilowatt hour?

2. The elevator in a certain school building requires a 30 horse power motor. If it exerts its full power for 20 minutes of each hour, 6 hours per day, for 20 days per month, what does it cost to run it at 5 cents per kilowatt hour?

3. A school auditorium requires 500 incandescent lamps, each using 0.25 ampere at 115 volts. What will it cost to light the auditorium for one hour, if the rate is 8 cents per kilowatt hour?

4. To charge an automobile storage battery requires 5 amperes at 8 volts for 15 hours. If this is done from a 110 volt alternating system, the efficiency of the converting mechanism being 30%, what will it cost, the rate being 4 cents per kilowatt hour?

5. An electric iron uses 6 amperes at 115 volts, a gas iron uses 8 cubic feet per hour. If electricity is 10 cents per kilowatt hour, and gas is $1.50 per 1,000 cu. ft., what is the difference in cost of a three hour ironing by the two irons?

6. A 1/10 H.P. motor requires 1.1 amperes at 115 volts. What is the efficiency of the motor?

7. A room is lighted by four lamps, each lamp using 0.3 ampere at 115 volts. How many watts are required? If the rate is 8 cents per kilowatt hour, what will it cost to light the room for three hours?

8. An electric flat iron has a resistance of 25 ohms, and is used on a circuit of 110 volts. How many calories are generated in one hour?

CHAPTER LIII

ALTERNATING CURRENTS

487. Importance of Alternating Currents.—In the early days of electric lighting, direct current generators were used almost exclusively. Of late, however, central stations are generating alternating current. This is because large alternating current (a.c.) generators can be built more cheaply than direct current (d.c.) generators, and because, thanks to the transformer, the alternating current can be transmitted with less loss of energy, due to heating of the wires, than direct current.

What two advantages have alternating currents over direct currents?

488. A. C. Generators.—You will remember that our simple loop of wire, fitted with collecting rings, and rotated between the poles of a magnet, gave an alternating current. The development of the alternating generator from this simple machine has followed the same lines as that of the d.c. machine. First came bipolar machines, then multipolar machines were used to cut down the necessary speed of rotation, until finally today we have machines capable of generating 45,000 kilovolt-amperes (Fig. 442).

There are two main differences between the d.c. and the a.c. generators: (1) alternating current generators (alternators) usually have a rotating field and a stationary armature, so that there is a better opportunity to insulate the armature windings; (2) since the current produced is alternating, it cannot be used to excite the electromagnets of the

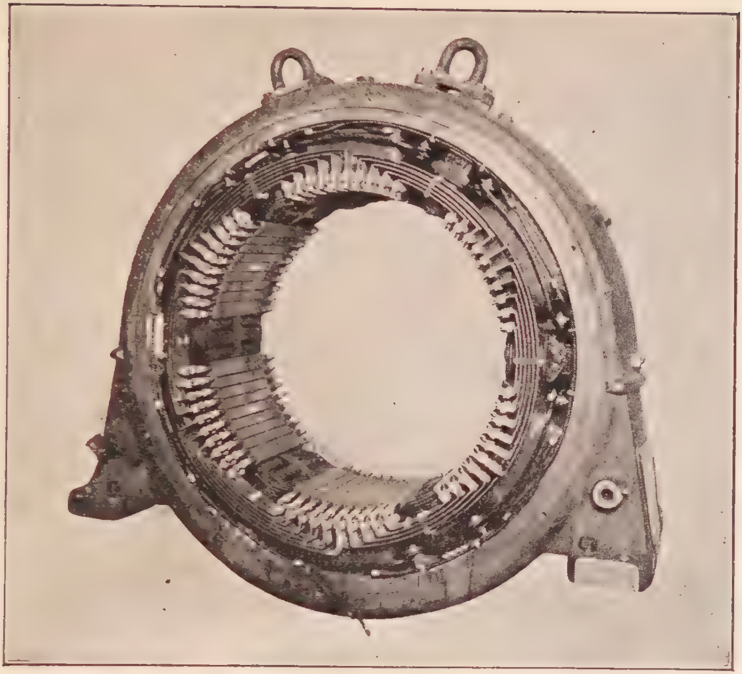

FIG. 442*a*. 3000-volt Generator Stator, Showing Fields and Connections

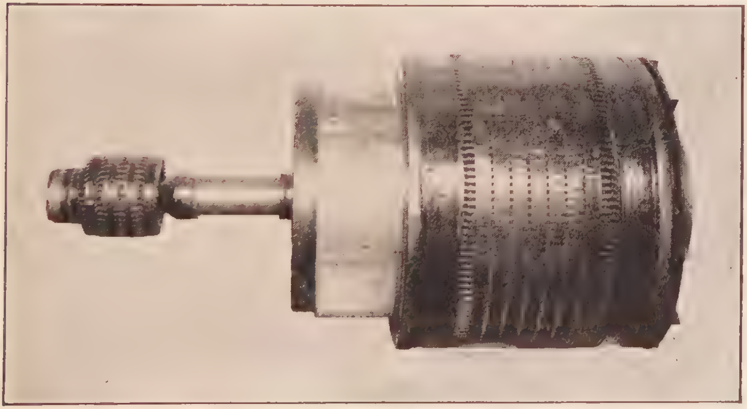

FIG. 442*b*. 3000-volt Generator Rotor with Exciter Armature

fields, and it is therefore necessary to provide a small d.c. machine to give direct current for this purpose.

A *cycle* is one complete back and forth alternation of the current. The *frequency* is the number of cycles completed in one second. The commercial frequency most used in this country is 60, except in long distance transmission, where a frequency as low as 25 is used.

What are the two main differences between an a.c. generator and a d.c. generator? Why is a separate machine needed to excite the fields? What is the frequency of a current? Define cycle. What frequency is most used in city lighting? Under what conditions is a low frequency desirable?

489. Transformers.—A transformer is a *voltage changer*. It does not alter the frequency of the alternating current, nor does it transform it to direct current. It is essentially a soft iron ring, with two windings, one on each side of the ring (Fig. 443). One of these windings carries the current the voltage of which we wish to change, the other winding carries the transformed current. The ratio of the new e.m.f. to the original e.m.f. is directly proportional to the number of turns of wire in the two coils. If we apply a voltage of 5,000 to a coil of 100 turns, and the other coil has 10 turns, the voltage of the current from it will be 500. A transformer used to raise voltage is called a *step-up transformer;* one used to reduce voltage is a *step-down transformer.* (Fig. 444.)

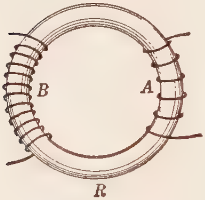

Fig. 443. Ideal Transformer

The great advantage of the alternating current is economy of transmission. If the alternator gives us 2,300 volts, a step-up transformer in the power house may raise this to 50,000 or even 150,000 volts. At this voltage the amperage is small, and therefore the heat loss (I^2Rt) in transmission is small, so that the copper wire used to carry the current may be small. The current at this tremendous potential is carried over long distances to substations, where it is stepped down to 2,300 volts, and then distributed to the user, where other transformers step it down to 110, 220, or 550 volts. The efficiency of the transformer is so high that we can afford these various transformations, and still lose only a little electrical energy. This makes it possible to generate the current wherever cheap power can be obtained, as at Niagara, and then transmit it to distant cities for use. Thousands of transformers are now used in radio receiving sets to amplify the variations in voltage.

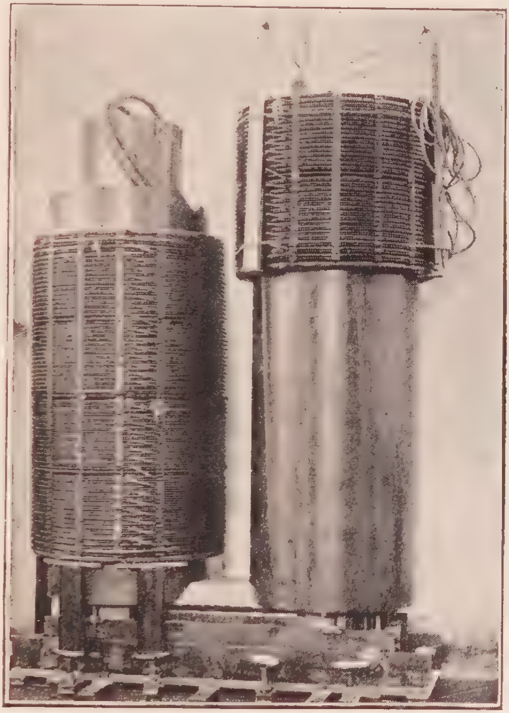

Fig. 444. Commercial Transformer. Assembly of Coils on Core

What is a transformer? How is it constructed? How may the voltage in the secondary be greater than in the primary? What is a step-up transformer? A step-down transformer? What is the advantage of a high voltage for the transmission of power? What kind of transformers are used in the power station? At the consumer's premises? Why is not much energy lost in these transformations?

490. Alternating Current Motors.—These are of various types, depending on the size required and the work to be done. It would carry us too far into advanced Physics to describe them in detail, so we shall simply give the different classes.

Series Motors.—These are constructed somewhat after the plan of the d.c. series motor and have nearly the same characteristics. They are used extensively on electric locomotives.

Synchronous Motors.—These resemble a.c. generators in their construction. Such motors are not self-starting, and are not used in small sizes, because of the difficulty of starting them, and because they must be started without a load.

Induction Motors.—These have two essential parts, the *stator,* which sets up a rotating magnetic field, and the *rotor,* in which induced or eddy currents are generated by the magnetic flux of the currents in the stator. Acting in accordance with Lenz's law (§ 471), these eddy currents tend to prevent relative motion of the rotating field and the rotor, and thus cause the rotor to follow the rotating magnetic field. Such motors are nearly constant speed motors, although the speed drops a little as the load is increased.

Can motors be operated by means of alternating currents? Mention three classes of a.c. motors. What are the advantages of the induction motor? What causes its rotor to turn?

491. The Telephone.—A telephone circuit is sometimes said to transmit speech. In reality it transmits alternating electric currents. Corresponding to the generator, transformer, and motor of an a.c. circuit, we have a telephone transmitter, an induction coil, and a telephone receiver. In *Alexander Graham Bell's* earliest telephone the transmitter and receiver were similar (in principle like the present receiver), just as a motor is only a generator reversed. Now a different kind of transmitter is used. It will be more easily understood if we first describe a simpler instrument called the microphone.

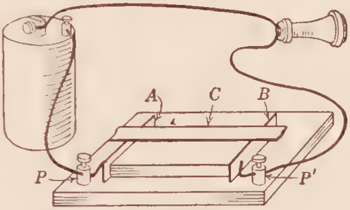

FIG. 445. Microphone

FIG. 446. Alexander Graham Bell (1847-1922). American born in Scotland, who invented the telephone.

The *microphone* consists essentially of two carbon rods, A and B, on a board, with a third, C, laid across them (Fig. 445). Connect A and B in series with a dry cell and a telephone receiver. The electric resistance at the contacts of C with A and B varies greatly when the pressure is changed, and so gives rise to variations of the current in the receiver, which emits a humming sound. If sound waves fall on the board, they set it into forced vibrations, and the receiver sounds. Microphones have been made so sensitive as to make the footfalls of a fly audible. The telephone *transmitter* uses carbon contacts in a similar way (Fig. 447*a*). A loose mass of finely granulated carbon, G, is confined between two carbon plates, C and C'. One plate, C, is fixed and the other, C', is connected to a thin iron diaphragm D. An electric current passes from C to C' through the granulated carbon. When you speak in front of the diaphragm, sound waves fall on it and cause it to vibrate. It exerts a varying pressure on the carbon grains, altering the electric resistance at their contacts, and thereby causing variations of the current.

The *induction coil* is a step-up transformer of a simple type, the primary of which is connected in the transmitter circuit and the secondary to the telephone line. It also serves to improve the quality of the sound heard in the receiver by cutting out a scratchy tone.

The *receiver* converts the energy of the electric currents into energy of sound waves. It consists (Fig. 447*b*) of a permanent magnet, *M*, with two soft iron pole pieces, *P* and *P′*, each wound with fine silk-

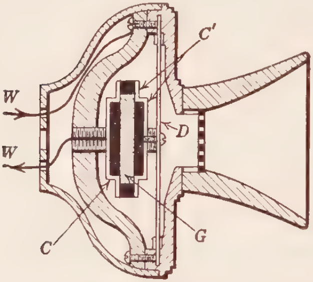

FIG. 447*a*. Telephone Transmitter

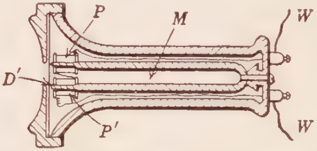

FIG. 447*b*. Telephone Receiver

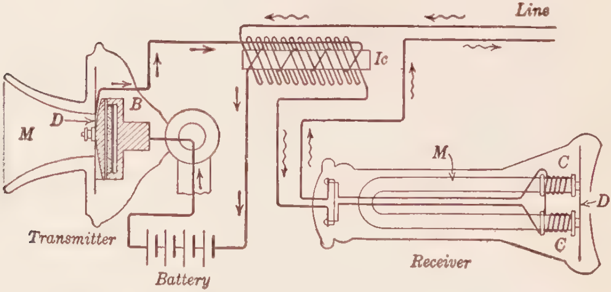

FIG. 447*c*. Telephone Line

covered wire. In front of the pole-pieces, but not touching them, is an iron diaphragm, D'. These parts are mounted in a hard rubber case. The windings of the poles are connected in series with the telephone line. The alternating (or pulsating) current in the line passes through the windings, and alternately increases and decreases the force with which the pole-pieces attract the diaphragm, which is thus set into vibration and reproduces any sound that falls on the transmitter.

In this brief account of the principles of the telephone the complex details of the telephone system of a large city have been necessarily omitted. (Fig. 447*c*.)

What are the essentials of a telephone circuit? Describe a microphone. What does it accomplish? How is the microphone transmitter constructed? Why does speaking in front of the transmitter change the current strength? What is the purpose of the induction coil? Describe the receiver. How does it operate?

EXERCISES

1. Mention some of the limitations and some of the advantages of the alternating current applied to commercial work.

2. What is a cycle in an alternating current? What do you mean by frequency?

3. Sketch, describe and explain the transformer.

4. How are transformers used commercially? For what purpose?

5. What is the difference between an induction coil and a transformer?

6. Upon what principle or fact does the operation of the telephone transmitter depend?

7. Explain the action of the telephone receiver.

8. Sketch and explain the operation of a complete one-way telephone system. Label the essential parts.

CHAPTER LIV

ELECTRIC WAVES

492. Waves.—You have learned that ether waves produce varying effects depending on their wave lengths. Very short waves (§ 337) are known only by their chemical effects, longer waves are light, and still longer waves (§ 271) radiant heat. Ether waves much longer than any of these can transmit electrical energy, and it is by their use that wireless telegraphy and telephony are possible. Just as a bell *oscillates* or vibrates and produces *waves* in the air, and these are *detected* by the ear, so wireless telegraphy requires an *oscillator, electric waves,* and a *detector*. Of the great number of devices that have been invented for these purposes we can refer to only a few here. The principles of electric waves were first worked out by Maxwell about 1870, but a method of generating them was not discovered until twenty years later.

FIG. 448. James Clerk Maxwell (1831-1879), great Scotch genius, discovered electromagnetic waves by mathematical theory

Are all ether waves of the same length? What is the difference between waves of light, heat, and electric energy? What agencies are needed for wireless telegraphy? Who worked out the principles governing electric waves?

493. Electric Oscillations.—As an analogy, which will help to make clear the meaning of electric oscillations, think of a U-shaped tube partly filled with mercury or water (Fig. 449). If it is tilted and quickly righted, the liquid will *oscillate*, or surge backward and forward between the two arms. The oscillations die down, or are *damped*, as it is called, owing to friction. By gently rocking the tube we can cause sustained or *undamped* oscillations of the liquid.

Joseph Henry found (in 1842) that the discharge of a Leyden jar is frequently oscillatory, that is, that the electricity surges backward and forward between the coatings a large number of times in a small fraction of a second, before the oscillations are damped out by the resistance of the circuit. Hertz made (in 1888) an oscillator in which two plates, *A* and *B* (Fig. 450), took the places of the two coatings of the Leyden jar. Knobs, *D* and *D′*, connected to the plates formed a discharger. When the plates were connected to the secondary of an induction coil in action, each spark between *D* and *D′* consisted of a large number of damped oscillations, the damping being due to the air resistance between *D* and *D′*. (If the resistance is too great, no oscillations take place.) Such oscillations start *electric waves.*

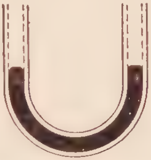

FIG. 449. Electric Oscillations Analogy

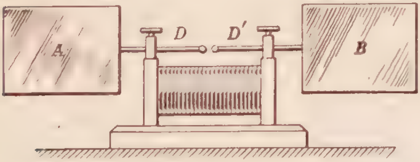

FIG. 450. Hertz Oscillator

What is meant by oscillations? What is the character of the discharge of a Leyden jar? Describe Hertz's experiments in the study of the discharge of Leyden jars. How are electric waves started?

494. Hertz's Detector.—Hertz found that, when electric waves fell on a circular loop of wire of proper dimensions with a spark gap (Fig. 451), they started oscillations around the loop and produced sparks at the gap. This was his detector.

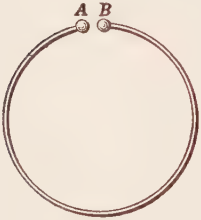

Fig. 451. Hertz Detector

A tuning fork can be set into vibration by sound waves produced by an exactly similar fork, but does not respond to vibrating forks of other pitches (§ 168). Similarly, the ring detector must be of such a size that it is *tuned* to the electric waves produced by the oscillator. This tuning for a particular wave length is now used with all detectors.

With his oscillator and detector Hertz studied electric waves in the laboratory, showing that they could be reflected and refracted like waves of light. He thus proved, experimentally, Maxwell's theory that light consists of electric waves.

What was Hertz's detector? Why must a detector be tuned? What did Hertz learn with his detector?

495. Marconi's Antenna.—Marconi connected a tall wire, called an *aerial* or *antenna*, to one side of an oscillator (Fig. 452), and another to a detector located a considerable distance away. He thus obtained waves that could be detected at a distance of several miles from the oscillator. The use of an antenna extended the size of the oscillator, just as a sounding board on which a tuning fork is pressed gives out a much louder sound than the fork alone (§ 190). Similarly, the antenna at the detector took in a large amount of electrical energy. This was the beginning of wireless telegraphy.

What is the purpose of the antenna?

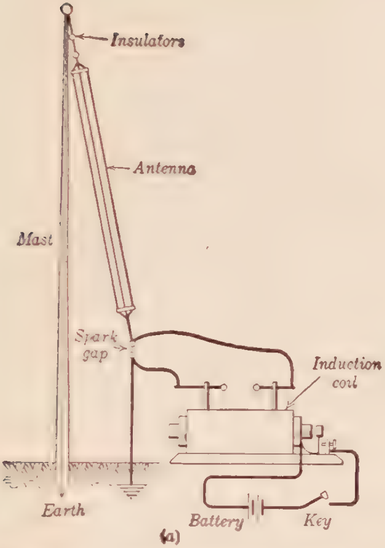

Fig. 452*a*. Early Marconi Sending Station for Wireless Telegraphy

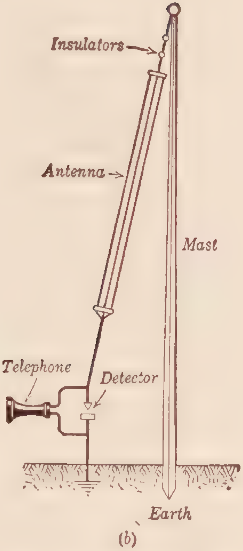

Fig. 452*b*. Early Receiving Station

496. Undamped Oscillations.—Much more energy can be poured into the waves if the oscillations can be kept up, that is, if they are undamped oscillations. An ordinary a.c. generator produces very slow oscillations in the a.c. circuit, only 60 per second. To speed them up, special generators have been constructed for wireless telegraphy. In the *Alexanderson alternator* there is an induction coil consisting of a primary and a secondary (Fig. 453) on the same axis. Between them pass iron teeth on a rotating wheel. Alternating currents of a frequency as high as 200,000 per second are induced. One terminal (the secondary) is connected to the antenna and the other to the ground.

What is the purpose of Alexanderson's alternator? How is it constructed?

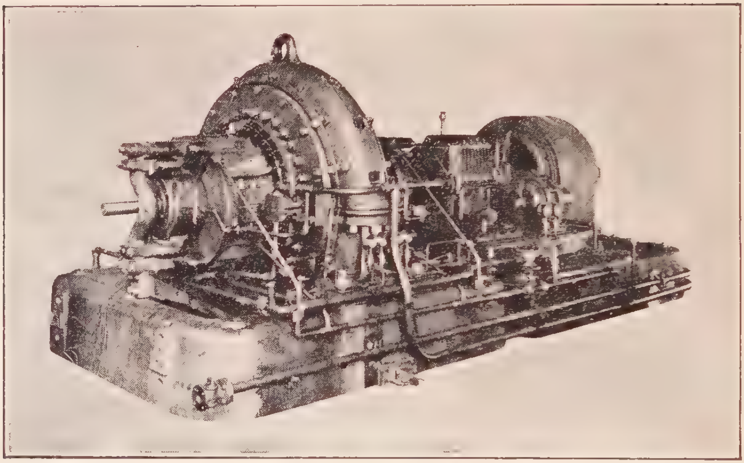

FIG. 453. 200 k.w. High Frequency Alternator

497. Crystal Detectors.—The detector that was chiefly used for several years consists of a piece of a crystal, such as silicon, molybdenite, or carborundum, in contact with a piece of metal. When the crystal is connected to the positive pole of a battery and the metal to the negative pole, a current will flow through the contact of metal and crystal, but when the connection is reversed practically no current will flow. If, therefore, we attempt to pass an alternating current through such a contact, only half of each wave will pass. The a.c. will be changed to a pulsating d.c. Thus the contact acts as an *electric valve* (§ 71) and is described as a *rectifier.*

This device is used as a detector by connecting it across part of the receiving circuit and then connecting a telephone in parallel with the rectifier. If waves of high frequency, say 100,000 or more, acted on the telephone without the rectifier being present, they would produce no effect, since its disk cannot vibrate so rapidly, and, besides, sounds of a frequency of 100,000 would be too high in pitch to be audible. But when the signals are sparks, each being an oscillatory discharge and giving rise to a short train of waves, the rectifier will rectify each group and each group will cause a click in the telephone.

Pressing the key at the sending station starts a train of electric waves through the ether. These, falling on the aerial of the receiving station, cause the telephone to hum. Dots and dashes are transmitted by varying the time that the sending key is depressed. Much more complicated circuits are used commercially. The above is only intended to explain the principle involved.

What is a crystal detector? What peculiarity does it possess? What is a rectifier? How is the detector used in wireless telegraphy? How is the telegraph code of dots and dashes transmitted and received?

498. **Electron Tubes.**—The oscillators and detectors mostly used now depend on an early discovery made by Edison, although its explanation was not known until much later. Edison made an incandescent lamp with a plate or electrode *p* in addition to the filament *F* (Fig. 454). When *P* was connected through a galvanometer *G* to the positive terminal of the lighted lamp, a current was obtained in the galvanometer, but there was no current when the connection was to the negative terminal. The electric current in the filament is a stream of negatively charged electrons. When the filament is hot enough, many of the electrons escape into the bulb. When *P* is at a positive potential relatively to the filament as a whole, a stream of electrons is attracted to *P* and flows from *F* to *P* and around the circuit through the galvanometer. When *P* is negative to the filament, no current flows because no electrons escape from the cold plate.

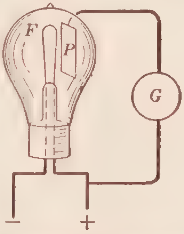

Fig. 454. Electron Tube

Describe the action of Edison's electron tube.

499. Electron Tube Detector and Amplifier.—A tube in principle like that used in the Edison effect, consisting of a hot filament and a plate in a vacuum, was used by Fleming as a detector. It conducts a current between the plate and the filament only when the plate is anode, since the current is carried by means of electrons from his hot filament. Hence with an antenna connected to the plate and the filament grounded, only the positive half of the a.c.'s from the antenna pass through, that is the tube acts as a rectifier, and a telephone between plate and filament responds. (Fig. 455.)

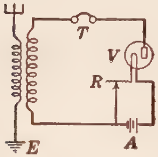

Fig. 455. Fleming Tube in Use As a Detector

This arrangement was greatly improved by DeForest by introducing a *grid* of wires between plate and filament. The antenna is connected to the grid, and a battery and a telephone or other receiver is connected between hot filament and plate, with plate as anode. Slight fluctuations of the potential of the grid, due to the antenna, have a marked effect in opposing or aiding the stream of electrons from the filament and thus cause fluctuations in the battery circuit. Hence this tube is a relay of practically zero inertia, or it amplifies small oscillations in the antenna into large oscillations in the battery circuit. By connecting several such in series the effect can be enormously multiplied. (Fig. 456*a*.)

How is the Fleming detector constructed? What addition did De Forest make? Compare the action of the tube to a relay. Why may it be called an amplifier?

500. The Electron Tube in the Radio Receiver.—This type of electron tube with the filament, plate, and grid is extensively used as a detector and as an amplifier in the latest broadcast receivers, of which there are many forms. The single circuit set employing only a detector is shown in figure

456*b*. The variable condenser *C* is used with the inductance *L* to tune the circuit to the frequency of the incoming waves which are picked up by the antenna. The fluctuations in potential of the grid *G* cause much larger fluctuations in the current through the plate circuit which includes the telephone receiver *T*.

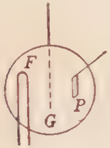

FIG. 456*a*. DeForest Tube with Grid

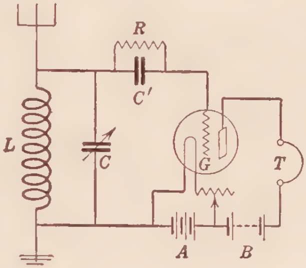

FIG. 456*b*. Simple Radio Set

In series with the grid of the detector is placed a small condenser *C′*, which is shunted by a high resistance *R*. This arrangement assists in building up a negative potential on the grid and thus helps to rectify the current.

If the telephone be removed, the primary of a step-up transformer inserted in its place, and the secondary connected to the grid of a second tube, the current fluctuations may be further increased. This may be repeated with a second transformer and a yet higher degree of amplification secured. Such a combination of transformers and tubes constitutes an audio frequency amplifier.

Sometimes one or more amplifying tubes are placed between the antenna and the detector where they are called radio frequency amplifiers. In this position in the circuit they are commonly tuned to the incoming waves by means of condensers, as was the detector circuit in figure 456*b*.

501. Electron Tube Oscillator.—The vacuum tube has been developed into an oscillator of great efficiency. Various arrangements are used, of which that shown in figure 457*a* is one of the simplest. *L* is an inductance and *C* a condenser connected to an antenna, and having a definite period of oscillation that can be tuned. *V* is the electron tube. The plate *P* is connected through a battery *B* and an inductance *L* to the hot filament *f*. This is called the *plate circuit*. The grid *G* is connected through an inductance *L* to the hot filament. This is called the *grid circuit*. The battery *A* keeps the filament *f* hot.

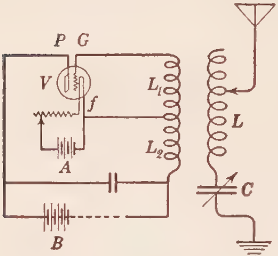

FIG. 457*a*. Vacuum Tube Oscillator

Any slight disturbance in *LC* produces slight oscillations, which act by mutual induction on L_1, producing slight oscillations of the same period. These, acting through the grid *G*, cause oscillations of the plate current which, acting through L_2, increase the amplitude of the oscillations in *L*, which again add to the oscillations in L_1, and so on.

502. Wireless Telephony.—In wireless telephony waves corresponding to audible sound of low frequency, e.g., 1,000, are superimposed on waves of high frequency, e.g., 50,000, and "modulate" the latter, that is, cause periodic changes in their amplitude without affecting their frequency. In figure 457*b* *A* represents the steady or unmodulated electric waves, *B* the sound waves of the voice, and *C* the modulated waves, the wave outline in *C* being of the same form as *B*.

The modulation is produced by means of combinations of vacuum tubes too complex, in general, for description here; but one comparatively simple arrangement may be outlined. An ordinary telephone transmitter current (§ 491) is amplified by an electron tube, and the circuit of the amplified current is connected in parallel with the battery of an electron tube oscillator (e.g., *B* in figure 457*a*) and thereby produces changes of amplitude of the oscillations in the antenna.

The receiver for such modulated waves is a rectifier, such as the crystal rectifier or a vacuum tube rectifier (§ 501). In the rectified current are oscillations of audible frequency, reproducing, through a telephone receiver, the vibrations of the voice at the transmitting end.

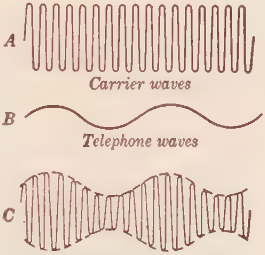

FIG. 457*b*.

What are carrier waves? What is a modulated wave? How does the modulated wave transmit the elements of the spoken word or the music? What is necessary in order to reproduce the actual sounds?

503. The Photo-electric Cell.—This device is an essential part of some recent important applications of physics. It consists of a vacuum tube (Fig. 458), of which the anode *A* is a loop of wire, while the cathode *C* consists of potassium deposited on the glass of the tube. The potassium has the property of emitting electrons when light falls on it. The electrons travel to the anode and so an electric current is created in the circuit. The strength of the current is proportional to the intensity of the light, and however small the current may be, it can be amplified enormously by the amplifying methods used in radio work (§ 500). The photo-electric cell is a kind of electron

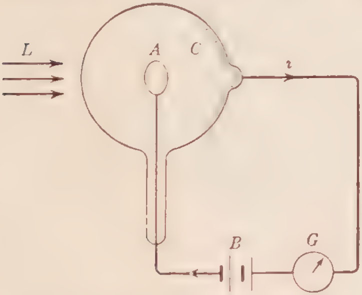

FIG. 458. Photo-electric Cell

eye that rivals the natural eye in sensitiveness. It can be made to detect a one-candle light at a distance of two miles, and it has been found very useful in studying the light from the stars.

What are the parts of a photo-electric cell? What is the property of the cathode? How is the cell used?

504. Television.—One of the recent marvels of applied physics is vision by telephone wires (or by wireless). A man *A* at the receiving end sees on a small "screen" a picture of *B*, who is at the other end, a hundred or a thousand miles away. The observing screen is a rectangular opening in a frame placed in front of a rotating disk (Fig. 459), which makes fifteen (or more) revolutions in a second. In the disk there is a ring of

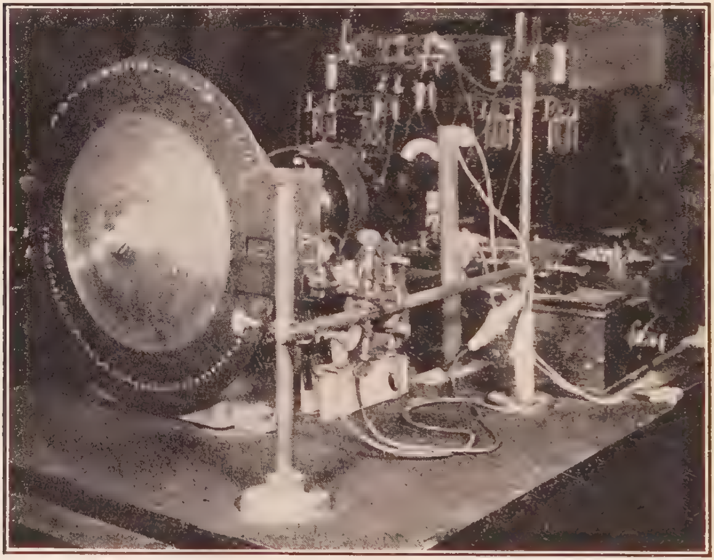

Fig. 459. Television; the picture is seen in the small square as the disk rotates

holes arranged eccentrically, and behind the screen there is a bright light. The flashes of light that come through the holes as they pass create the picture observed by *A*.

At the transmitting station each small part of *B's* face is illuminated in turn by a narrow beam of light that flashes downward in successive parallel lines. This is accomplished by a "scanning" disk with a ring of holes, arranged as in the observing disk, so that each part of the face is illuminated fifteen times in a second by light that passes through a hole. Each small part of the face, when the light falls on it, reflects an amount of light proportional to the natural whiteness of that part. The light so reflected fells on a photo-electric cell, which produces a rapid series of currents, the strengths of which correspond to the degrees of whiteness of the different small parts of the face. The currents so produced are amplified and transmitted to the receiving station, where they control the intensity of the light behind the receiving disk.

Evidently the two disks must keep step exactly, so that each element of the face shall be reproduced at exactly the right element of the screen. This is accomplished by synchronous motors (§ 490) which drive the two disks. But such motors are subject to slight variations of speed. So each is assisted by a much smaller motor, operating at 2000 cycles, these two motors being on a single current transmitted by the line.

The picture can also be projected on a large screen by a modification of the method. Moreover wireless waves can be used, instead of currents on a telephone line, to control the light and regulate the motors.

How are the holes in the rotating disk of the receiving apparatus arranged? What effect does this produce as the disk rotates? What does the scanning disk do? How are electric currents produced at the transmitting station? How do these currents produce the picture?

CHAPTER LV

CONDUCTION THROUGH GASES

RADIOACTIVITY

505. Discharges in Gases.—The most striking of all electrical phenomena and the first observed by primitive man (though not then known as electrical) is lightning, with its brilliant light and loud sound. It is an electric discharge through the air. Conduction of electricity in a wire is a silent procession of electrons, all marching in one direction. Conduction in a solution consists of two processions of slowly-moving ions, or charged atoms, marching in opposite directions. The movement would not begin unless there were already some ions in the liquid before the e.m.f. is applied, constituting a state of "spontaneous ionization" of the liquid (§ 404). A discharge in the form of a spark between two plates in air also consists of two opposite streams of ions, though the negative ones move faster than the positive ones. It also requires some initial spontaneous ionization of the air, and the cause of this has proved a fascinating problem that has only recently been solved (§ 510). These natural ions get up very great speeds compared with those in solutions, owing to the high potentials necessary, and so they are able to smash a few molecules with which they collide. The new ions thus produced attack other molecules and produce more ions, and so on. The process, once started, is almost instantaneous, and it makes the air such a good conductor that there is a sudden rush of electricity through the gas. This takes place along some line of least resistance, more or less zigzag, and so we have an electric spark.

To produce a spark 1 mm. long in air requires about 3000 volts between the electrodes. In a tube from which most of the air has been removed, so that the remaining molecules are quite far apart, a discharge takes place at relatively low voltage. The first few ions can dash farther and get up much greater speed before colliding with molecules. Thus the ionization necessary for a discharge in the form of a spark is obtained with a much weaker field. When the amount of the air in the tube is more and more reduced, by use of an air pump, the ionization throughout the tube becomes more complete, and the spark widens out into a continuous glow that fills the whole tube. These same explanations apply to any gas or vapor, and you can now give a more complete account of the action of the mercury vapor lamp.

Is it easier to send a spark through air of ordinary density or through rarefied air? What change in the character of the discharge takes place as the air becomes rarefied?

506. Cathode Rays.—When the pressure in a tube containing air is reduced to about 1/1,000 of an atmosphere, an electrical discharge through it causes a glow that fills all the tube, except a small dark space near the cathode. As the pressure is further reduced the dark space grows in size. When the pressure has been reduced to about 1/1,000,000 of an atmosphere (Fig. 460), the dark space occupies the whole tube. But there is still a discharge of some kind, for the end of the tube opposite the cathode C is covered by a bright phosphorescence. This is due to particles of some kind that shoot straight across the tube from the cathode. They are called cathode particles or **cathode rays,** and the tube is called a *cathode ray tube.* They do not pass through metal and a metal cross (Fig. 460) throws a shadow S.

When a magnet is moved around near a tube in which there are cathode rays, the phosphorescent glow on the glass opposite the cathode moves about on the glass. The cathode rays are therefore deflected by a magnet, the manner of their deflection being the same as if they were currents of electricity. By noticing how the spot *S* moves, when acted on by the lines of force of the magnet, and then applying the rule stated in § 471, it has been found that the cathode rays are **negatively charged particles.** By a careful study of the action of cathode rays in magnetic and electrical fields, the masses and velocities of the particles have been found. The particles are always of the same mass, each about 1/1845 of an atom of hydrogen. These minute negatively charged particles are **electrons.** Their velocity in a cathode ray tube is enormous, usually not much less than the velocity of light.

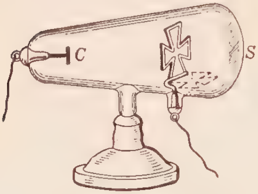

FIG. 460. Cathode Ray Tube

How are cathode rays produced? What effect does a magnet have upon them? What does this show as to their character? Define electron.

507. X-Rays.—Wherever the cathode rays strike they produce a new kind of rays, called **X-rays** or **Roentgen rays,** after their discoverer (1895). To get these X-rays, it is best to let the cathode rays strike on a platinum target *P* (Fig. 461*a*) in the middle of the tube. The X-rays spread in all directions from the target. Such a tube is called an *X-Ray tube.* The X-rays, while not themselves visible, pass out through the glass and produce remarkable effects.

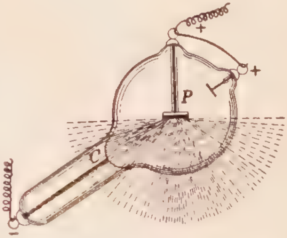

FIG. 461*a*. X-Ray Tube

X-rays have the same effect as light on a photographic plate. They cause vivid fluorescence when they fall on barium platinocyanide, calcium tungstate, zinc sulphide, and many other substances. A *fluoroscope* (Fig. 461*b*) for observing the effects of X-rays is a box with a phosphorescent screen as one side, and two holes to look through in the opposite side. When X-rays fall on the screen, the eyes placed at the holes see vivid fluorescence all over the screen. If various objects be brought between the screen and the X-ray tube, it will be seen that the X-rays pass freely through many substances that are opaque to ordinary light, partly through others, and through others not at all. Thus the X-rays pass through the flesh, but only to a slight extent through the bones of the hand. These differences simply depend on the densities of the substances. This explains why the X-rays can be used to locate bullets or shrapnel in the body, to find defects in internal organs of the body, to examine the roots of teeth, to test masses of metal for internal flaws, and to do many other wonderful things. (Fig. 462.)

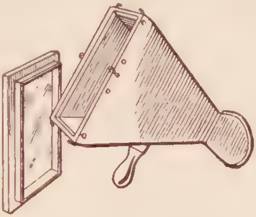

Fig. 461*b*. Fluoroscope

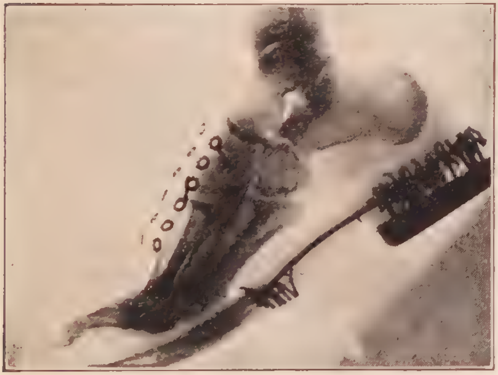

Fig. 462. X-Ray Picture

Another important property of X-rays is the effect they have on the electric conducting power of a gas. If you turn an X-ray tube so that the stream of X-rays falls on a charged electroscope, the electroscope will be discharged as if it had been touched by a conductor. The air is ionized by the X-rays, that is, many of the molecules are broken up into charged atoms, called ions. The ions of opposite signs to the charge of the electroscope are attracted to the plate and they neutralize the charge of the electroscope.

X-rays are a form of light, but they are of much shorter wave-length than the violet at the end of the visible spectrum (§ 333). They are "splashes in the ether," when the cathode rays are suddenly arrested by the target in the X-ray tube.

What are X-rays? How are they produced? What effects may X-rays produce? How may X-rays be used to locate metallic substances in the body? How do X-rays differ from ordinary light rays?

508. Radioactivity.—Within a year of the discovery of X-rays, another important discovery was made. Becquerel found (in 1896) that compounds of uranium affect a photographic plate much as light does. Madame Curie found the same thing to be true of thorium. These substances are described as **radioactive.** Madame Curie extracted from pitchblende (an ore containing much uranium) minute quantities of a new element, now called **radium,** which is a million times more radioactive than uranium. Radium is now mostly obtained from carnotite, a uranium ore occurring in Colorado. Other highly radioactive substances, such as *polonium* and *actinium,* have been found. Radium may be taken as typical.

What is meant by radioactive substances? Who discovered radium?

509. The Explosion of Atoms.—Important as was the discovery of radioactivity, it led to a still more important discovery, made by Sir Ernest Rutherford. Radium gives off "rays" of three kinds: alpha rays, beta rays, and gamma rays.

The *alpha rays* are positively charged particles. When caught in sufficient quantity they form a gas. This gas has been tested by the spectroscope (§ 336) and has been found to be the element *helium*. Alpha particles are helium atoms carrying positive charges. The *beta rays* are simply electrons, and, of course, are negatively charged. The *gamma rays* are X-rays, but are much more penetrating than ordinary X-rays. They can pass through a foot of iron. (Fig. 463.)

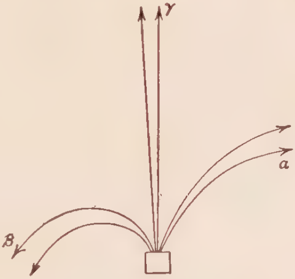

FIG. 463. α, β, and γ Rays

These particles and rays are due to an explosion of the radium atom. In the break-up, a small part of the radium atom is shot off in the form of alpha and beta particles, leaving behind an atom of another radioactive element. In the course of time, perhaps after a few seconds, perhaps only after hundreds of years, this new atom also explodes, and an atom of a third radioactive element is left, and so on. The radium atom itself came from an earlier explosion, and that from one still earlier. Tracing the line back we come finally to uranium. The life history of an atom of uranium is a long series of explosions, like that of a rocket traveling by explosions repeated at intervals. In the end it becomes an atom of lead, where, so far as is known, it has reached a stable condition. Radium is merely one of the temporary atoms in the line of descent from uranium to lead.

Radium also gives off *heat*. A gram of radium emits more than 100 calories in an hour. In three days it emits as much heat as does the burning of a gram of coal, and it continues to do this for hundreds of years. This heat comes from the gradual disintegration of the radium atoms. When alpha particles and beta particles are shot off from atoms in the interior of a piece of radium, most of them are arrested by impact on other atoms of the radium itself, and their kinetic energy is transformed into heat.

All this suggests the question, whether the atoms of the more familiar elements also break up spontaneously. Perhaps they do, very slowly, but if so the particles emitted have such comparatively small velocities that the process has not yet been detected. Rutherford has, however, found evidence that when alpha particles are fired at atoms of nitrogen (and various other substances) the atoms of nitrogen break up into atoms of helium and hydrogen. In this subject it is probable that we are only at the beginning of discoveries of vast importance.

Name the three kinds of "rays" given off by radium. Distinguish between them. What causes them? What change takes place in the radium after a long time? What other peculiar power has radium? What relation has all this question to the possibility of changing one element into another? Do we yet know all about this?

510. Cosmic Rays.—One of the most recent discoveries is that X-rays come to us from the distant stars or nebulæ. Their existence is shown by the way in which they ionize air. It has long been known that an electroscope, however well it may be shielded, even when it is inclosed in a thick metal vessel, always slowly loses its charge. After all other possible causes had been considered and eliminated, it was agreed that the leakage of charge must be due to X-rays from some unknown source, present everywhere. It has now been found, by work on mountaintops and in airplanes, that these rays must be coming to us from some source outside the earth and its atmosphere. It has been shown that they do not come from the sun or any of the planets. They must therefore be given off by the distant stars or nebulæ. They are therefore called *cosmic* rays. The presence of these rays everywhere accounts for the spontaneous ionization of the air referred to in § 506.

Cosmic rays are so penetrating that they are capable of passing through six or seven feet of lead. This indicates that their wave-length is far shorter than that of any X-rays or gamma rays previously known. To what actions in the stars and nebulæ these rays are due is not certain, but they are probably the result of atomic changes, such as explosions of atoms into their constituent electrons and protons, or the opposite process of union of these constituents to form atoms.

CONVERSION TABLES

Length

To change	*Multiply by*
Miles to kilometers	1.609
Yards to meters	0.914
Inches to centimeters	2.54
Kilometers to miles	0.621
Meters to yards	1.093
Centimeters to inches	0.393

Surface

Sq. yards to sq. meters	0.836
Sq. inches to sq. centimeters	6.451
Sq. meters to sq. yards	1.195
Sq. centimeters to sq. inches	0.155

Volume

Cu. yards to cu. meters	0.764
Cu. inches to cu. centimeters	16.387
Cu. feet to liters	28.317
Gallons to liters	3.785
Pounds of water to liters	0.453
Cu. meters to cu. yards	1.308
Cu. centimeters to cu. inches	0.061
Liters to cu. feet	0.035
Liters to cu. inches	61.023
Liters to gallons	0.264
Liters of water to pounds	2.204

Weight

Tons to kilograms	907.184
Pounds to kilograms	0.453
Ounces Avoirdupois to grams	28.349
Grains to grams	0.064
Kilograms to tons	0.001
Kilograms to pounds	2.204
Grams to ounces Avoirdupois	0.035
Grams to grains	15.432

For more accurate conversion tables refer to the Smithsonian tables. In ordinary computations, three significant figures are quite sufficient.

METRIC SYSTEM TABLES

Linear Measure

Millimeter,	mm., =	0.001	meter
Centimeter,	cm., =	0.01	“
Decimeter,	dm., =	0.1	“
Meter,	m., =	1	“
Kilometer,	km., =	1000	“

Surface Measure

Square millimeter,	sq. mm., =	0.000,001	square	meter
Square centimeter,	sq. cm., =	0.000,1	“	“
Square decimeter,	sq. dm., =	0.01	“	“
Square meter,	sq. m., =	1	“	“

Cubic Measure

Cubic millimeter,	c.mm., =	0.000,000,001	cubic	meter
Cubic centimeter,	c.c., =	0.000,001	“	“
Cubic decimeter,	c.dm., =	0.001	“	“
Cubic meter,	c.m., =	1	“	“

Capacity Measure

1 cubic centimeter,	c.c., =	0.001	liter
1,000 cubic centimeters,	c.c. =	1	“
1 kiloliter,	kl., =	1000	“ = 1 cubic meter

Weight

Milligram,	mg., =	0.001	gram
Centigram,	cg., =	0.01	“
Decigram,	dg., =	0.1	“
Gram,	g., =	1	“
Kilogram,	kg., =	1000	“

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